1.0

1.1

1.25

4.5
5.0
5.6
6.0

2.8
3.2
3.6
4.0

1.4

2.5

2.2

2.0

1.8

1.6

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AGARDograph 125

DTIC

MAR 2 1982

H

Subatmospheric Decompression Sickness in Man

AGARDograph Number
One Hundred and Twenty-five

Subatmospheric Decompression

Sickness in Man

The Advisory Group for
Aerospace Research and
Development. NATO

3

"Au milieu de notre enthusiasme pour cette entreprise grandiose nous ne manquerons pas de reporter notre pensée vers P. Bert, ce grand physiologiste, qui, dans ces questions, mérite à jamais notre profonde reconnaissance."

(Closing sentence of von Schrötter's paper to the 5th Physiological Congress, 1901 on the physiological background to the balloon ascent of Berson and Süring).

4

Author

D.I. FRYER
Royal Air Force

PRECEDING PAGE BLANK-NOT FILMED

Accession For

NTIS GRA&I

DTIC TAB ☐

Unannounced

Justification

By

Distribution/

Availability Codes

Avail and/or

Dist Special

A

DTIC

COPY

INSPECTED

2

7

Contents

Acknowledgements

The preparation of this book has been made possible by the facilities granted to the author during his service in the Medical Branch of the Royal Air Force. Not only has it been possible to conduct research into the effects of high altitude in the decompression chambers at the RAF Institute of Aviation Medicine, but colleagues throughout the service have made data available and have referred cases for opinion, and colleagues within the Institute have contributed immeasurably by their willingness to join in discussions on this puzzling subject. To the long-suffering but always good-humoured sufferers from 'bends' and other manifestations, my thanks can never be adequately expressed.

It is impossible to acknowledge in detail all those service colleagues to whom a debt is owed. However, exception must be made in the cases of the late Air Vice-Marshal W. K. Stewart, CB. CBE, AFC, MB, BS, MRCP, Director of the Institute from 1945 until his death in 1967 and his successor and former deputy, Air Commodore H. L. Roxburgh, CBE, Ph. D., BSc., FRCP(Ed.), FRAeS. Among physicians, Air Vice-Marshal Sir Aubrey Rumball, KBE, FRCP (Retd), Group Captain J. N. C. Cooke, OBE, MD, FRCP and Group Captain H. B. Kelly, MVO, MD, FRCP. have been particularly generous in freely providing access to their cases and their profound expertise, and among pathologists, Group Captain J. K. F. Mason, MD, FC Path. has unstintingly allowed the writer material and advice.

Access to material has been freely given by many, including Professor W. Blackwood, Professor A. C. P. Campbell and Professor A. C. Lendrum in Great Britain, and Professor Elbel in Bonn, Federal Republic of Germany. Thanks are also due to Dr. E. Roebuck and Mr. W. Waugh for drawing attention to Case 28. Above all, the staff of the U. S. Armed Forces Institute of Pathology, during the period of tenure of office of Colonel F. M. Townsend. USAF, MC, as deputy director and director, not only allowed the writer to examine notes and sections, but also generously gave specimens of material from all U. S. cases.

The subject of this monograph is one which has attracted the attention of many workers throughout the world and it has been my privilege to discuss theories, exchange data and share enthusiasm with many. It is not possible to name them all, but particular mention is due to Dr. John Cotes, who first introduced me to the subject, Dr. Webb Haymaker of the NASA Ames Research Center, Moffett Field, California, Dr. Charles Berry of NASA, Houston and Professor François Violette of the French Air Force. The author's knowledge of the problems of compressed air illness is due mainly to the stimulating experience of membership of the Medical Research Council Panel on Decompression Sickness under the chairmanship of Professor D. N. Walder. In particular, Professor Roland Barnes and Dr. Mary Catto have contributed immeasurably to the understanding of underlying processes of aseptic necrosis of bone, and the staff of the Royal Navy Physiological Laboratory, Alverstoke, have always made me feel at home in discussing diving problems. In

Summary

Ascent to altitude or exposure to artificially reduced atmospheric pressure may lead to the development in man of a wide range of symptoms and signs. Rarely these have been followed by the occurrence of shock, occasionally fatal.

The clinical and pathological aspects of the altitude form of decompression sickness are here described and discussed, and an attempt is made to elucidate those factors influencing susceptibility.

Possible mechanisms are discussed, the relevant literature reviewed and original experiments are cited. Cases seen by the author are described in detail where they contribute to the tasks of characterisation of the illness, the investigation of cases, the differentiation from other conditions and the assessment of possible sequelae.

Theoretical and practical aspects of prevention and treatment are described.

1

Introduction

'Man-Made' Diseases

Man, through his own endeavours, has extended his capability to combat environ-
mental hazards to health far beyond the range of his innate physiological adaptive
systems. By the use of natural, and later, synthetic materials, he has extended
his habitat into areas of the earth otherwise too hostile for survival. He has learned
to combat disease processes and their causative agents. At the same time he has
extended his ability to explore; both by increasing the range of his travels, on land,
on the sea, under the sea and, most recently, into and beyond the atmosphere and
by increasing the speed capability of his vehicles.

These continuous processes of invention and exploitation have brought their penalties.
In the sociological sphere, group and race rivalries are often stimulated by com-
petition in travel and exploration and the results of such clashes have become
increasingly destructive to the participants as weapon technology has developed.
On an individual scale, man has brought on himself hazards to health which have
hitherto not existed. There are no natural counterparts of acute radiation injury,
high frequency electrical energy effects, the toxic effects of some elements which
normally do not exist in a free state and perhaps most important, the poisoning by
many thousands of synthetic chemical compounds.

Atmospheric Pressure Changes

A further category of injurious activities is man's manipulation of his environmental
pressure. In nature he can certainly injure himself, even fatally, by either reduc-
tion or augmentation of ambient pressure. Thus he can suffer mountain sickness
by climbing too high and he can crush his thoracic cage by too deep a breath-holding
dive . Since 1783, when both the hot-air 'Montgolfiere' balloon and the hydrogen
'Charliere' balloon were invented, the range of exploration has been extended
beyond the altitude of the highest peaks of the land-mass, and the invention of the
diving bell (traditionally by Alexander the Great in the fourth century B.C.) has
opened up the depths of rivers, lakes and seas beyond the capability of the naked
diver.

The invention of the air pump by von Guericke in 1650 allowed the exposure of
animals and materials to both supra and subatmospheric pressures, but apart
from the classical experiments of Robert Boyle little attention was paid to the
biological sequelae of pressure changes. It was some 180 years before humans
were exposed to artificially raised and lowered pressures. With this came the
first recognition of a dangerous and even fatal effect, inexplicable except in terms
of some inherent result of pressure reduction after exposure to compressed air.

The fascinating story of the recognition and investigation of the disease variously called 'compressed air illness' or 'caisson sickness' has been recounted by many authors, particularly Leonard Hill (1912) and John F. Fulton (1948).

The recognition that a similar ill-effect might result from exposure to subatmospheric pressure, even when full oxygenation is ensured, has an intriguing history, some aspects of which will be dealt with in Chapter 2. The establishment of the existence of a risk stimulated little interest until a practical situation arose in which men were likely to be exposed in considerable numbers as an essential part of aviation progress, both peaceful efforts towards aircraft development and military preparations for aerial combat. The latter became more and more important and when war finally came, in 1939, efforts to solve the problems of high altitude flight were accorded high priority in medical research. The resultant studies have been reviewed many times, particularly in Fulton's compilation (1951) and the summary of German Aviation Medicine in World War II (1950).

Current Status of Subatmospheric Disorders

It may be thought that as advances in aircraft technology have provided reliable pressure cabins and operational pressure suits, the hazards to man would have decreased. This is not so, except possibly in terms of numbers exposed. In four fields of activity the physiological effects of subatmospheric decompression are a serious impediment to progress. These fields are:

1) Military aviation, in which effective cabin pressurisation cannot be guaranteed or may be precluded for certain reasons.

2) Civil aviation, wherein, with development of higher-flying passenger-carrying aircraft, large numbers of persons may, albeit rarely, become exposed to very low ambient pressures as a consequence of malfunctions or failure of engines or airframe.

3) Space Flight, where structural considerations lead commonly to a choice of a low-pressure environment.

4) Research, in which exposure to simulated altitude is made, either as a technique for academic studies, such as respiratory physiology and hypoxia investigations, or as a part of applied programmes aimed at the investigation of conditions likely to be encountered in space or conventional flight.

The Problems

Firstly, it is essential that the syndrome or syndromes of decompression sickness should be clearly described and categorised.

Secondly, the conditions under which their appearance becomes a possibility should be clearly defined and the relationship between all relevant environmental and individual factors and the incidence of clinical manifestation should be established.

Thirdly, the treatment of the acute condition should be investigated and the best methods defined.

Fourthly, the avoidance of the disease by a community and by an individual should be investigated.

Fifthly, the education of those concerned with exposure, both as persons at risk and persons in authority, should be ensured.

Approaches to their Solution

The literature abounds with different approaches to the problems listed above. They range from the mathematical, the theoretical, physical and statistical to the frankly fatalistic. Continuing interest in the subject is a reflection of the incompleteness of the success of these studies.

The most striking single reason for the paucity of our knowledge is the absence of satisfactory experimental material other than large human groups. Small animals are probably totally resistant to straightforward subatmospheric decompression. Such manoeuvres as prior exposure to high pressure (Leverett, Bitter and McIver, 1963) additional hypoxia and exercise (Philp & Gowdey, 1964) mechanical violence (Whitaker, Blinks, Berg, Twitty and Harris, 1944) and selective breeding for obesity (Antopol et al. 1964) introduce complications which make the relevance of associated studies to human exposure extremely difficult to assess.

Large animals have been claimed to be susceptible. Often this has been observed in conditions of grossly disturbed physiology as a result of operative procedures (Armstrong, 1939). In other cases, such as in the work of Malmejac (1948), positive results have been claimed with dogs, but experience of other workers (Violette, personal communication) has shed doubt on these observations. It is quite possible that hypoxia played a part in the manifestations described. The only study on sheep (Miller, 1944) was very briefly reported and has never been repeated. The degree of gut distension in ruminants, when decompressed, is such that many complications may arise from diaphragmatic displacement, venous obstruction etc. which have no relevance to the human situation.

The Clinical and Epidemiological Approach

The writer has adopted almost exclusively the method of analysis of incidents and the compilation of data from organised large-scale exposures of aircrew groups, aimed primarily at selection. It has been the writer's fortune to see the great majority of cases of decompression sickness arising in the R.A.F. over a period of fifteen years. A combination of direct observation, *post hoc* investigation and collaboration with clinicians has allowed a compilation of case histories on which a comprehensive survey of the manifestations may be based and the differential diagnosis established.

These observations on in-flight cases are augmented by the investigation of large numbers of cases reported during decompression testing of aircrew. The analysis of tests allows insight into the multiplicity of factors influencing the occurrence of the condition.

2

History

Introduction

It is not only instructive, and often humbling, to delve into the history of a subject.
It is also frankly exciting.   One develops a 'feeling' for the topic as the picture
slowly grows clear.

The historical aspects of ascents to altitude and simulated ascents by decompression
have inspired several writers to compile historical surveys.   In particular, the
subject has been excellently dealt with by the late John F. Fulton (1948) and more
recently by Andersen (1965).   However, there is much evidence of transcription
without search and in particular, the medical literature has been quoted much more
freely than that of aviation in general.   In a personal survey of early writings, a
much clearer picture has emerged and it is with a particular emphasis on 'new'
discoveries that this chapter will deal.

Physical Aspects of Altitude

Eight years after Toricelli in 1640 had discovered the means whereby atmospheric
pressure may be measured, Blaise Pascal (1623-1662), a theologian and experi-
mental physicist, arranged for a simple toricellian barometer to be carried up the
Puy de Dôme.   The height of the mercury column diminished, indicating that the
pressure exerted by the atmosphere was less at altitude.   This observation
coupled with the discovery by Robert Boyle (1627-1691) of the relationship between
pressure and volume in gases, laid the foundation of the scientific study of altitude.
The invention of the air pump by von Guericke, in 1650, allowed simulation of
altitude and Robert Boyle was soon to exploit the version of the pump made for
him by Hooke for studies on living things.   His "The Spring of the Air", published
in 1660, contains accounts of a multitude of studies on animals and later, in 1670,
he described the now famous '... bubble moving to and fro in the waterish humour
of one of its eyes', when he decompressed a viper in his 'Exhausted Receiver'.
No attempt seems to have been made to subject man to the 'tortures' of the
'exhausted receiver', although Boyle wrote of his ambition to have a chamber of
appropriate dimensions.

In 1783 the brothers Montgolfiere and Professor Charles invented balloons which
gained their buoyancy from hot air and hydrogen respectively.   The opportunity
was soon seized by scientists to exploit this new tool and what has aptly been
called 'balloonomania' became the obsession of the age.   It was soon proved that
the air at altitude retained sea level composition.   The Toricellian barometer
was used to gauge height (Fig. 2-1) and extravagant claims about altitudes attained
began to appear.   Blanchard made an assertion that on 20th November, 1785, he
achieved 32,000 feet, but this was dismissed by his contemporaries.

b*

Dramatic accounts were published in the ensuing years, describing a host of symptoms experienced by 'aeronauts'. It took the genius of Paul Bert (1833-1886) to unravel the confused stories of mountaineers and balloonists and by assiduous experimentation he revealed the role of oxygen lack and the value of oxygen therapy in decompression to subatmospheric pressure.

Junod, in 1833, was probably the first to conduct experiments on man in a pressure vessel. He described his chamber as a copper sphere, only 4 ft. 3in. in diameter, but an illustration to one of his reports (Fig. 2-2) shows an intermediate cylindrical section.

Paul Bert also supplemented his animal experiments by researches on himself. His two-compartment decompression chamber (Fig. 2-3) today is proudly preserved in the entrance hall to the Paris laboratories of the Centre des Enseignements et Recherches en Médecine Aéronautique. In 1874, breathing oxygen, he subjected himself in this chamber to a pressure equivalent to 28,000 feet (248 mmHg) with no ill effect (Fig. 2-4).

Bert also studied and brilliantly disclosed the cause of symptoms in miners and divers emerging from compressed atmospheres. They had been known to be subject to severe illness, sometimes fatal, and many physicians had sought in vain to understand the physiology of 'mal des caissons' since the first reports of Triger (1845) and Pol and Watelle (1854). Bert showed that decompression from raised pressures gave rise to evolution of bubbles in tissues and fluids, and postulated that these were the aetiological agent of the clinical syndromes seen in man. Strangely he apparently failed to foresee the possible evolution of bubbles on decompression from sea level.

The Ill-Effects of Altitude on Man

As balloonists ascended to greater heights, they began to encounter the ill-effects of the combination of low pressure and cold. Their accounts are highly dramatic and, one suspects, over colourful. This is particularly striking to one who has experienced the amnesia of altitude hypoxia. In 1803, Count Zambeccari and Dr. Grassati both became unconscious when their hot-air balloon reached a great altitude, this was watched by their colleague Pascal Andreoli. In 1808, Andreoli and a Signor Briochi ascended to some 30,000 feet according to the evidence of the former; once more his companion lost consciousness and Andreoli himself lost the use of his left arm.

In 1862, the great meteorologist and later, president of the Royal Aeronautical Society, James Glaisher, F.R.S., ascended in his gas-balloon with Mr. Coxwell, its manufacturer. They rose rapidly from their launching site in Wolverhampton, intent on continuing their programme of scientific observation commenced some three months earlier. According to their published account, at an altitude coresponding to $9\frac{3}{4}$ inches of mercury (28,000 feet by present definition) Glaisher progressively lost the use of his arms, his legs, his power of speech and ultimately his vision. Coxwell, in a similar but lesser plight, climbed into the rigging and pulled the valve cord with his teeth. Both recovered and Glaisher (1871) later claimed to have reached 36,000 or 37,000 feet. Although this story is oft-repeated it is probably unreliable. Apart from the extreme altitude claimed, the detailed account of the two mens' behaviour is both improbable and unlikely to have been recalled. However there is nothing to suggest that either suffered from more than the effects of cold and hypoxia.

P
(mm Hg)
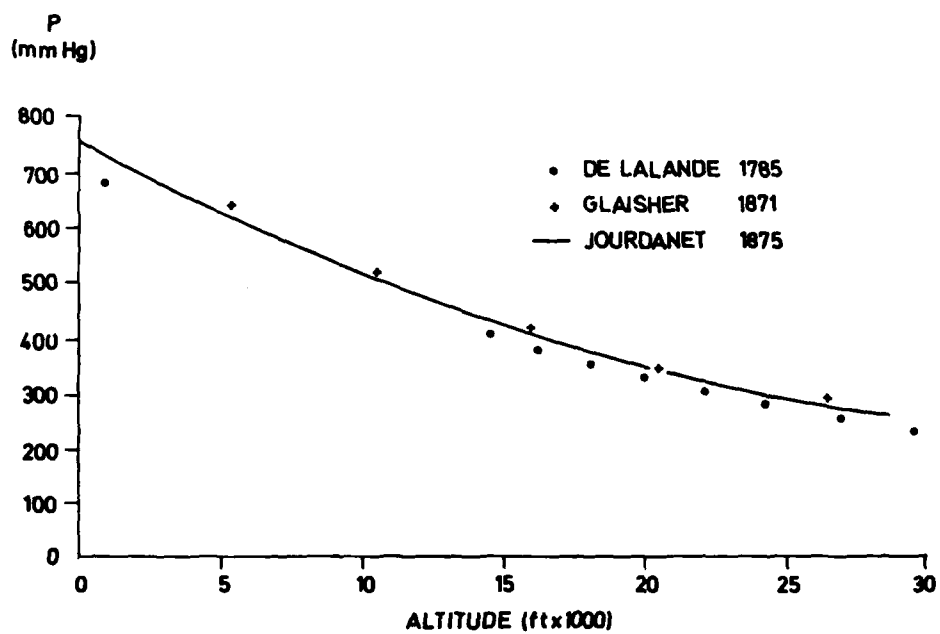
Fig. 2-1   Eighteenth and Nineteenth Century altitude/pressure data (derived
from Glaisher, 1871 and Bert, 1877).
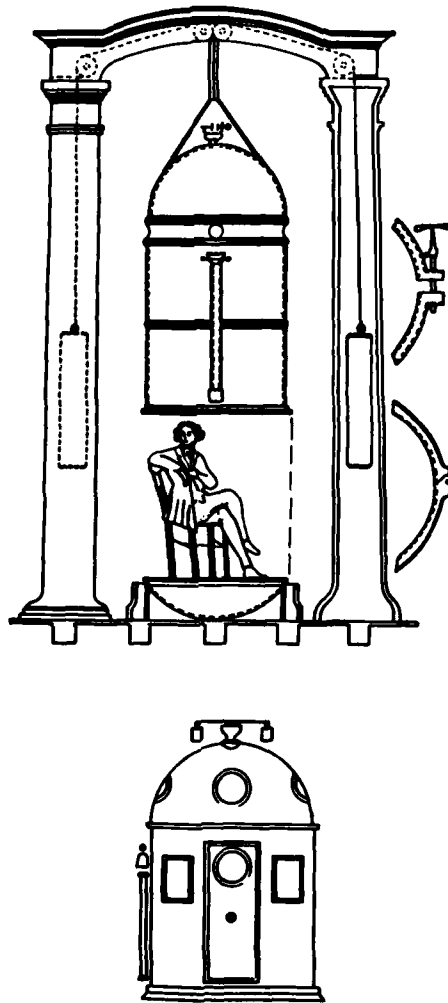
Fig. 2-2   Tracing of the illustration to Junod's paper of 1835, illustrating
(above) a chamber for exposure of man to raised or reduced
atmospheric pressure and (below) a design for a chamber for
large-scale therapeutic use.
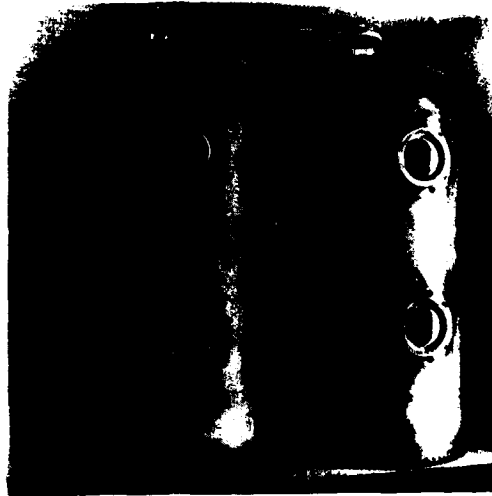
Fig. 2-3   Paul Bert's altitude chamber, 1967. (Photograph by courtesy of the Centre d'Enseignement et de Recherches de Médecine Aeronautique, Paris).
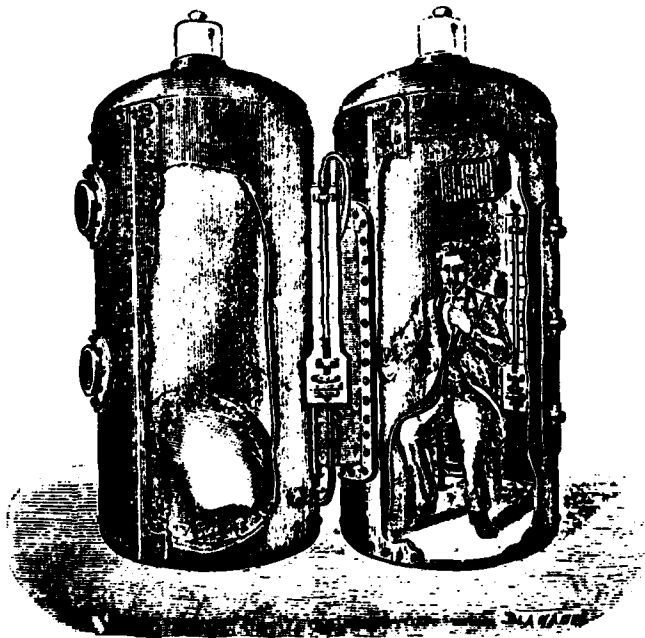
Fig. 2-4   Paul Bert's altitude chamber, 1874.

More heedful of physiological opinion, Gaston Tissandier had sought the advice of
Paul Bert and together with his colleagues Sivel and Croce-Spinelli, had experienced
the effectiveness of oxygen in combating the simulation of altitude in Bert's decom-
pression chamber before attempting a high altitude flight. Thus, on March 22,
1874, they used an oxygen/air mixture stored in flexible gold-beater's skin bags
during an ascent to 24,000 feet. On April 15th, 1875, they again ascended in
the balloon 'Zenith', but disaster overtook them. Profoundly affected by hypoxia
and cold they became incapable of reaching the mouthpieces of their apparatus and
all three became unconscious. On recovering from his torpor, Tissandier found
his colleagues dead. He later estimated that they had reached 28,000 feet,
certainly he claimed to have seen the mercury of the barometer fall below 280 mmHg
(25,000 feet). They were the first known victims of acute altitude hypoxia.

Did they perhaps suffer from an altitude equivalent of caisson sickness? No contem-
porary thought seems to have been given to this question.   J.S. Haldane (1935)
claimed that there was evidence of 'bends' in the tales told by early balloonists, but
the writer has been unable to find a convincing account.   The element of paralysis
described by Glaisher and Tissandier is a little suspicious, but these pioneers
were profoundly hypoxic for long periods, and extremely cold.   It is not unlikely
that the limbs actually feel 'useless' under such circumstances.

The first account of an altitude response inexplicable in terms of hypoxia which
the writer has been able to discover, is in hitherto neglected brief communication
to the 5th Congress of Physiology in 1901 by the Viennese, E. von Schrötter, who
had accompanied Herr Berson and Professor Süring, of the Prussian Meteor-
ological Institute, in ascents from Strasbourg.   These pioneers used oxygen
stored in cylinders and had, with this equipment, reached a height of almost 35,000
feet (10,500 metres).   The greatest actual height reached by von Schrötter was a
little under 25,000 feet but he had taken the scientists and himself to an atmospheric
pressure of 230 mmHg (30,000 feet) in a decompression chamber in Berlin.
He discussed "..... the question of whether in the course of high ascents there
was a fear of gaseous embolism as established by Paul Bert". "..... he himself
had been a victim, in the pneumatic chamber, of a marked paralysis which luckily
was no more than passing, but accompanied by tonic convulsions of the upper
extremities and the masseters, becoming above all dangerous because of a tonic
contraction of the diaphragm and impossibility of breathing." (von Schrötter,
1901).   This occurred, in spite of the use of oxygen, during and following an ascent
to 30,000 feet in fifteen minutes.   von Schrötter attributed the incident to bubble
formation.   The paralysis and spasm are hard to analyse, but the respiratory
symptoms are doubtless those now known as 'chokes' (see Chapter 3).   The signifi-
cance of these observations appears to have gone unnoticed until now.

In 1906, von Schrötter (Hermann, though presumably the same person as referred
to with the initial E. in 1901) published a book on oxygen in the prevention and
treatment of decompression sickness.   In this, he tended to discount decompression
sickness as the cause of the above incident, stating (Page 243, paragraph 3 - Page
244, paragraph 3 incl):-

"I must further report one incident which occurred during one of our experiments and
which throws light on the subject from another angle; this incident requires a more
detailed explanation.

During one of our experiments in which we had reached a pressure of 230 mm in
about fifteen minutes, it happened that I was suddenly unable to breathe just as
I had taken the tube into my mouth for oxygen respiration.   At the same time an
extremely painful sensation of tightness around the lower thoracic margins made
itself felt, as if caused by an iron band, in addition to the existing cramp of the diaphragm,

it was impossible to use sufficiently the auxiliary respiratory muscles. The legs failed completely and became immobile. I was unable to get up. My arms were extended forward, and the hands were held in a writing-pen position; it was impossible to move the fingers. At the same time I was struck by a cramp of the jaw, as a consequence of which I bit and broke the glass mouth-piece and injured my lips slightly; my facial expression was reported as drawn, cyanosis did not exist. All this happened while Berson and Süring felt perfectly well and endeavored to resuscitate me. It is further noteworthy that my mind was perfectly clear and that I was fully capable of judgement during those five minutes that the condition lasted; I even thought of the possible cause of the existing phenomena and reflected whether to ask my colleagues to start artificial respiration.

After applying cold water and increasing the pressure again by about 100 - 150 mm, the phenomena receded completely during the course of about ten minutes. At first I could breathe again, although there still existed a certain tension in the area of the diaphragm; then the cramps receded and the mobility of the lower extremities recurred. A sensation of warmth, a peculiar pressure towards the periphery and a feeling of pins-and-needles in the legs occurred simultaneously; the stiffness of the fingers disappeared last.

The fact that the cessation of my respiratory action was not caused by a tightening of the position of the lungs - as may perhaps be explained by the followers of this theory - is clearly demonstrated by the additional phenomena in the muscular apparatus, by the cramps and the paralysis of the lower extremities. During a further experiment which was carried out a few days later with a lowering of the pressure by 250 mm although the decrease occurred somewhat slower, the phenomena failed to appear as was the case during the previous experiments. The complete well being of my companions is also evidence against assumptions of this kind. This also suffices to reject the assumption that the diaphragm was perhaps hindered in its function by a distension of the stomach with subsequent pressure on the solar plexus. I add that my abdomen did not show any inflation and that the possibility of emptying the stomach by vomiting existed.

However, the phenomena differed essentially from those symptoms which we know arise during progressive rarefication of air, and which we had observed repeatedly during the previous experiments. During the incident in question, cramps with unrestricted consciousness were the dominating symptom although of course paralysis and indeed the disappearance of cerebral functions usually characterise the condition. The disturbances could therefore not simply be seen as symptoms of anoxyhaemia. Considering the short time of decompression, one was compelled to think of one possibility which we have not yet considered in this context: the possibility that the syndrome was caused by a pathological de-gasification process, in that free nitrogen could have appeared in the circulatory system because of the speed with which the decompression took place. It would have led to an embolic process and therefore initiation of cramps just as we have seen with regard to caisson workers. An explanation in this direction seemed to me even more probable as I remembered a workman J.J. who was struck by similar respiratory disturbances after leaving the lock. This interpretation of the cramps and paralysis symptoms as they occurred in me, seemed to then the most probable one - as I have advocated in an earlier publication and I believed thereby to have proven that gas embolism can arise in man with too rapid decompression from normal air pressure.

The fact that under these conditions free gas bubbles can occur in the blood vessels and that they can cause disturbances has been established by animal experiments. But this happens only when the decompression to low values occurs in such a manner that the nitrogen is released in sufficient quantities; the speed of

decompression which is necessary for this must be very large and much greater
than the one with which we had decompressed in the above experiment, so that
the more detailed assessment of my case made me doubt whether the explanation
which I had given at the time was the correct one".

Boycott and Haldane, who at that time were laying down the foundation of all subsequent
practical work on the prevention of caisson sickness, nevertheless themselves
thought "... the risk of caisson disease at very low pressures ought to be taken
into account." (Boycott and Haldane, 1908).

Hill and Greenwood (1909) subjected animals to pressures as low as 50 mmHg,
at which death was to be expected in spite of the administration of oxygen, total
ambient pressure being too low to allow oxygenation of the blood.   They saw bubbles
in the heart of one rabbit after death, but made no reference to possible relevance
to ascents by man to lesser altitudes.

A correspondent signing himself E.L.W. wrote to the aviation magazine 'Flight'
in 1910 "I listened recently to an interesting discussion on deep-sea diving. It
was pointed out that all descents and ascents had to be made very slowly, since
a too sudden increase, or decrease, of pressure on the human body was attended
with fatal results.   The idea immediately presented itself that this state of things
would also obtain in the air.   Assuming that this is so and in view of the altitudes
recently attained by aviators, it is a point that would seem to call for some atten-
tion .....   I write as one who has no practical knowledge of the subject and who
therefore asks the opinion of those who have".   The writer, who almost certainly
was referring to a lecture given by Leonard Hill to the British Association, was
reassured by the editor that, because of the lower density of air than water, "...
much quicker changes of altitude may be made in the air than in water, without
serious effect."   This type of reassurance recurs in the literature, as we shall
see, for some twenty-seven years in the face of many relevant observations to the
contrary by experimenters and practising aviators.

The great American respiratory physiologist Yandell Henderson raised the query
about the possibility of the occurrence of a 'caisson disease' equivalent when he
wrote in 1917 that such an event was unlikely with the then attainable rates of ascent,
although he was at pains not to refute the concept out of hand.   He retained his
position in 1919, writing" ... it is essential, however, that the pressure with which
the tissues are in equilibrium should have been lowered considerably more than half
its absolute amount in a few seconds."   He then pointed out the impossibility of
achieving such a rate of ascent to the necessary 20,000 feet.   Here he clearly was
alluding to the 'half absolute' threshold so elegantly demonstrated for raised pressure
conditions by Haldane and others (1907) but he could have had no basis for his
period of 'seconds'.   The founder of British aviation medicine, Martin Flack, in
the same year, 1919, also drew attention to "articles on so-called 'flying sickness'
which have appeared in various periodicals."   He went on, more rashly than did
Henderson, to deny bubble formation as a mechanism and stated "This is not the
case," and later, "In diver's palsy and caisson disease one is dealing with a
reduction of pressure of from two to five atmospheres, whereas in flying one is
generally dealing with at the most a diminution of pressure of a little more than
half an atmosphere and certainly always less than one atmosphere, which is easily
within the margin of safety for the rate of decompression in compressed air work."
Thus two great authorities in their own fields laid down false bases for scepticism
which persisted for a very long time.

During the 1914-1918 war, many experiments were carried out in the air and in
decompression chambers, including Paul Bert's original vessel (Marchoux and
Nepper, 1919), but no hint of altitude effect due to evolution bubbles emerged.

Instead, there was an emphasis on hypoxia and a very nebulous concept of 'mal des aviateurs' pursued for many years by Cruchet and Moulinier (1920).

That all was not well might have been suggested by an experience reported by Beyne in 1923, when a 'healthy and very fit' pilot, apparently adequately provided with oxygen, collapsed suddenly at 36,750 feet, to recover on descent to some 24,500 feet, whilst still receiving the same oxygen supply.

In 1927, an American Army Captain, Hawthorne Gray, who had a consuming interest in altitude equipment, attempted an altitude record in a balloon. His efforts gained little attention and no mention appears in the medical literature. In fact his own national aviation press virtually ignored him, even when his second attempt ended in tragedy when his oxygen line was severed at some 42,000 feet and his dead body was returned to earth in the basket below his torn balloon. However, a French account of his first flight is of great interest. It seems that he reached about 40,000 feet and was perfectly fit when, as he threw overboard an empty oxygen cylinder to lighten the balloon, he was seized with a violent pain in his chest, which forced him to valve the gas from the balloon and make an emergency descent. This became so rapid that he had to jump from the basket at 8,000 feet, using his parachute. Ironically his altitude record, variously given as 42,030 and 42,060 feet was not homologated, because he did not land in the gondola. Surely here is a true case of 'chokes'.

In 1930 Béhague and Garsaux, who had established, in 1925, a first-class and very large decompression chamber at Le Bourget, Paris, wrote an account of a simulated ascent by a test pilot, preparing for an attempt on an altitude record. This man, aged 42, was taken to 45,000 - 47,000 feet at which height, in spite of administration of oxygen, he must have been hypoxic. (The original paper gives an altitude of 13,800 m. and a pressure of 10 cm of mercury; modern tables give the latter as equivalent to 47,000 feet (14,325 m.) whereas 13,800 m. (45,275 ft) corresponds to 109.1 mmHg). Suddenly he complained of violent pain in an arm. He wrote a note and held it to the port-hole (no voice communication was possible). The pain disappeared but the same arm (the right) suddenly became useless and limp, and fell to his side. The chamber was fairly rapidly 'dropped' by the admission of air and he had almost recovered by the time he reached ground level, but weakness persisted for many hours. At the time the incident was attributed to hypoxia. This seems unlikely in the light of re-appraisal. Firstly, the symptoms and signs are not characteristic; secondly, in spite of the altitude claimed to have been reached, gross clinical hypoxia can be ruled out if the man was capable of writing.

In the same year, 1930, the Dutch doctor, Jongbloed, reported to the 5th International Congress of Aerial Navigation on experiments which he had been carrying out on himself and his colleagues for two years, but which had not been published except in a doctoral thesis. He took his decompression chamber to 124 mmHg (he referred to this as being equivalent to 14,000 m. (45,900 feet) whereas by present standards this pressure would be expressed as equivalent to 13,000 m. (42,650 feet)). He and his colleagues noted, repeatedly, pain in the joints - wrist, knee, fingers, hip, shoulder, heel and foot. In a penetratingly clear analysis Jongbloed substantiated his assertion that "These phenomena are analogous with those found in men after rapid decompression from a high atmospheric pressure, i.e. light cases of the caisson sickness."

This work gained little publicity and even such conscientious and experienced workers as Barcroft, Douglas, Kendel and Margaria (1931) failed to associate pain in the knees during exercise at simulated altitude with caisson disease.

We next come to a protracted phase of claim and counter-claim. Strohl, in a thesis published in 1932, denied the possibility of decompression sickness (he had not apparently heard of Jongbloed's work). This is understandable since his ascents apart from those carried out on animals were never to less than 330 mmHg (i.e. never above 21,500 feet). Some practical aviators could have answered differently. Although C.F. Uwins had, after several attempts, raised the World Altitude record for aircraft to 43,976 feet in September 1932, he is adamant that at no time did he experience any symptoms other than cold, not surprising in an open cockpit with an air temperature as low as -45°C (Uwins, personal communication). However, the British team who were the first to fly over Mount Everest in 1933 wrote, confusing the aetiology, "Another physiological difficulty threatening the high-altitude aviator, is the air pressure which supports the small blood vessels of the body becomes so much diminished that these tend to burst. This is a real danger in the case of those past middle age or in the case of extreme heights at any age, tending to cause unconsciousness or acute and violent pains similar to those experienced by divers, who come up to the surface too rapidly" (Fellowes et al., 1933).

Sir Leonard Hill extended his work on simulated altitude in the early 1930s, attempting to define the maximum altitude to be reached when breathing oxygen (Hill, 1932 and 1933). This work was in part carried out at the Royal Aircraft Establishment, Farnborough and at Messrs Siebe Gormans where he collaborated with Sir Joseph Barcroft, Sir Robert Davies and Wing Commander (later Group Captain) Struan Marshall, Director of Research in the R.A.F. Medical Branch. In 1933 they took a Mr Eric Taylor, who was reponsible for the operation of the Farnborough chamber, to a pressure of 114 mmHg (44,250 feet). He became pale, but was obviously reasonably clear mentally as the illustration of his handwriting at 37,000 feet showed (Hill, 1934). As the ascent continued he became ashen, jactitated and dropped his pencil and paper; all attributable to a low inspired oxygen tension. He also complained of "some ache in the muscles of the front of the arms which disappeared before the pressure had returned to normal", probably 'bends' pain.

Unfortunately, Struan Marshall chose to follow the example of his predecessor, Flack, in denying on theoretical grounds the possibility of decompression sickness. In 1934 he wrote "It will, however be realised that this syndrome results from rapid release from great pressures, and it is this combination that effectively prevents it from applying to aviators, because the maximum amount of decompression in flying is less than one atmosphere, and the time necessary to reach an altitude equivalent to this [sic] is vastly greater than is necessary for the quick diffusion of dissolved gases through the lung. In any case it is a fact that no phenomenon resembling caisson disease has ever been observed in an aviator", (cited by Japp, 1935). This is all the more strange in the light of the recollection by Dr. Struan Marshall himself (personal communication, 1966) that he had several times experienced severe pain in both knees in the decompression chamber. He attributed this at the time to aggravation of old injuries. Sir Leonard Hill supported Marshall (Hill, 1935) but J.S. Haldane in open discussion thought decompression sickness at altitude possible, although unlikely owing to the nitrogen washing out effect of oxygen breathing (Haldane, 1935).

Meanwhile, according to Sergeyev (1962), the Soviet research worker Strel'tsov had, by 1934, established the occurrence of limbs joint symptoms at and above 33,000 feet and in the USA, Armstrong and Heim had seen cases of joint pain, collapse and convulsions, "acute pulmonary oedema" and crepitus apparently due to bubbles in a flexor tendon sheath (Armstrong and Borum, 1938, Heim 1937-38). Garsaux in 1936 classified 'mal des altitudes' as (a) Euphoric, (b) Convulsive, (c) Arthralgic and (d) Syncopal. The arthralgic form he noted to include severe

pain and cramps in and around joints, worse in fatigued joints and commoner in untrained subjects. The condition was commonest with rapid ascents and sufferers recovered quickly on descent. The statement, in the same paper, that there was no fear corresponding to that for deep divers must be taken to imply that the paraplegic form of caisson sickness was not anticipated to occur. Marshall by this time had slightly modified his tone, but still thought bubble formation unlikely "... in a healthy experienced pilot at any rate of ascent or descent now practicable" (Marshall, 1936).

The record-breaking Italian pilot Pezzi was certainly aware of altitude effects when he wrote, in 1937, that in extending flights above 16,500 to 26,400 feet beyond 1½ hours, pain in the limbs commonly occurred and could become intolerable (Pezzi, 1937). He also added a new symptom to the literature, migraine accompanied by severe fatigue, after such flights. He also noted that work affected joint symptoms; prolonged pressure on the rudder-bar causing leg pain and pressure on the control column giving rise to pain in the hand. That these were not merely fatigue or muscular strain is indicated by his observation that the symptoms eased or disappeared during descent.

Bergeret (1937) described severe joint pain, including two incidents affecting a colleague who had pain in the right shoulder, extending down the arm, causing complete loss of use of the arm. The symptoms arose at 30,000 feet and cleared during descent at between 24,000 and 20,000 feet. He commented on Jongbloed's discoveries of 1928-1930 and stated, with great honesty that "A la vérité l'étiologie, de ces manifestations nous échappe encore complètement".

With the acceleration of research associated with the political tensions of 1938-1939, reports began to accumulate and the occurrence of symptoms analogous to caisson sickness was universally acknowledged. Remarkably clear accounts of the symptoms were given by Matthews (1939) from Farnborough, Hornberger and Benzinger (1942) working in Rechlin, Germany and Rosenblum (1943) in the Soviet Union.

The risk of paralysis was referred to by Boothby and Lovelace (1938) when they described an ascent to 35,000 feet by a 'well known physiologist' (later revealed to be Dr. Heim) which resulted in complete, but fortunately reversible, paralysis from the waist down. The possibility of a fatal outcome was, most surprisingly, first mentioned in a popular book written specifically for aviators (Grow and Armstrong, 1941), stating that "... delay in treatment ... which, if ignored, may result in paralysis, unconsciousness or death". Zim (1943) reiterated the warning in a similarly popular book. In the same year the first recorded fatality, in fact, occurred.

The Terminology

The derivation of various popular and scientific synonyms for various signs and symptoms will be dealt with in the succeeding chapters. The general nomenclature of the syndromes resulting from pressure reduction is dealt with here. The terminology is indeed confusing. It has recently been considered by Andersen (1965), but even his comprehensive review is incomplete. To assist the reader, terms and their derivation are listed below and definitions attempted for those to be used later in the text.

'Caisson Disease' was coined by Smith in his monograph in 1873, written as a prize essay and describing the cases occurring during the building of the Brooklyn Bridge, New York. The term "caisson" is the name given to the pressurised structure used in the erection of the bridge piers. The German equivalent is 'Caisson-krankheit', the French 'Maladie des caissons' and the Italian 'Malattia dei cassoni'.

Surprisingly the earlier writers of monographs, Foley (1863) and Jaminet (1871) had not attempted to coin a term for the condition they described. Armstrong, in 1938, erroneously introduced an apostrophe into the term, it becoming 'Caisson's disease' - a remarkable pseudo-eponym. 'Compressed Air Illness' was favoured by Snell (1894), writing of the Blackwall tunnel under the Thames. Luftdruckerkrankungen (Heller, Mager and von Schrötter, 1900) is the German equivalent. Gerbis and Koenig (1939) preferred Drucklufterkrankungen. 'Caisson Sickness' was used as the title of his monograph by Sir Leonard Hill, (1912). 'Divers' Palsy' was an old term revived by Haldane et al in the Admiralty report on Deep Water Diving (1907). 'Tunnel Disease' was used by Corning of New York in a paper published in 1890. 'Aeropathy' was suggested by Erdman in 1907, but the term did not gain common usage.

'Aeroembolism' was coined by H.G. Armstrong in his textbook, 'Aviation Medicine' (1939). In 1941, in Grow and Anderson's book it gained an umlaut to become aeroëmbolism, a refinement not affected by later authors. It was the first term coined specifically for the subatmospheric syndromes.

'Decompression Sickness' is of indeterminate origin. Perhaps the first use is by Matthews in 1939, and the coining of the term has been attributed to his colleague, Dr. E.A. Carmichael. The German term 'Druckfallerkrankheit' introduced by Hornberger and Benzinger in 1942 has been claimed by Andersen as the origin of the English equivalent, whereas it clearly post-dates 'decompression sickness'.

'Dysbarism' was introduced by Adler in his 1950 monograph and the term is gaining in popularity. His sub-terms 'hypobarism' for a discrepancy of pressure in the direction ambient less than tissue and 'hyperbarism' for the reverse have never been adopted.

'Hypobarogenic Pneumatosis' is a term offered for consideration by Hall in 1955. Even he did not use it again.

'Aerebullosis' was also offered by Hall in 1955. He is alone in using it. Although reasonably euphonous, it has the demerit of mixed Greek and Latin roots (aer - Greek; e - Latin; bull - Latin; osis - Greek).

'Pompholyhemia' according to Hall (1955A), was proposed by Harvey as a term denoting bubble formation in blood.

'Barotrauma' is of uncertain origin. It has the merit of implying damage due directly to pressure effects.

'Mechanicobaropathy' has been proposed by Andersen in his 1965 review, as a term serving to discriminate between direct pressure effects and those due to bubble formation. It seems to have no advantages over 'barotrauma' and its derivations such as pulmonary barotrauma, and is too polysyllabic to be likely to gain favour.

Definitions

In this monograph it is the author's intention to use the terms:-
'Decompression Sickness' to denote those signs and symptoms associated with reduction of atmospheric pressure (from super-atmospheric levels or from one atmosphere) and not apparently due to the expansion of trapped or enclosed gas and not primarily due to oxygen lack.

'Barotrauma' is used to denote damage due to expansion of trapped or enclosed gas already present as such and not evolved from solution.

Table 2-1. The Standard Atmosphere

Altitude		Pressure	
feet	metres	mm. Hg.	atmospheres
Sea level	0	760.0	1.0
2,000	609.6	706.6	0.930
4,000	1219.2	656.4	0.864
6,000	1828.8	609.1	0.801
8,000	2438.4	564.5	0.743
10,000	3048.0	522.7	0.688
12,000	3657.6	483.4	0.636
14,000	4267.2	446.5	0.588
16,000	4876.8	411.9	0.542
18,000	5486.4	379.5	0.499
20,000	6096.0	349.3	0.460
22,000	6705.6	320.9	0.422
24,000	7315.2	294.6	0.388
26,000	7924.8	270.0	0.355
28,000	8534.4	247.1	0.325
30,000	9144.0	225.7	0.297
32,000	9753.6	205.9	0.271
34,000	10363	187.5	0.247
36,000	10973	170.5	0.224
38,000	11582	154.9	0.204
40,000	12192	140.7	0.185
50,000	15240	87.02	0.115
60,000	18288	53.73	0.0707
70,000	21336	33.14	0.0436
80,000	24384	20.44	0.0269
90,000	27432	12.62	0.0166
100,000	30480	7.52	0.0099
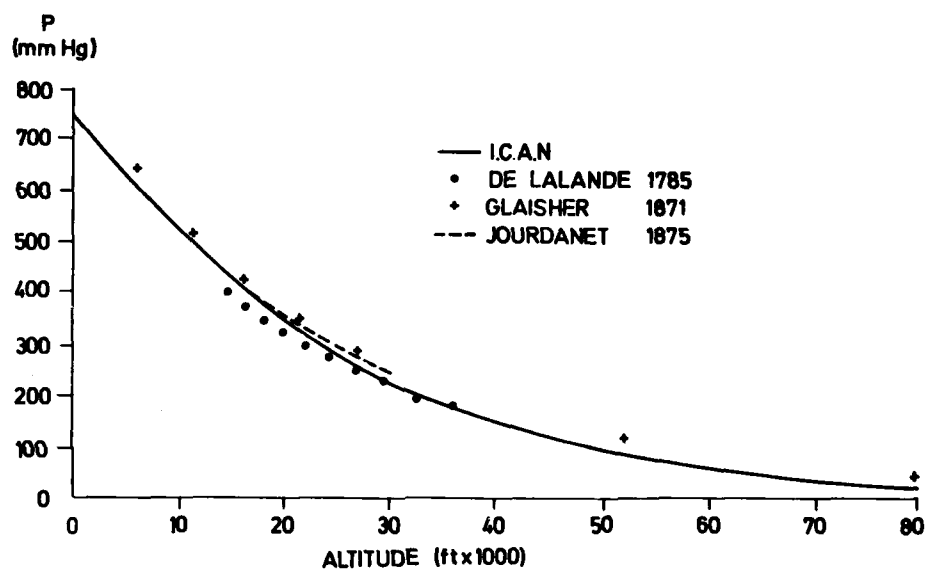
Fig. 2-5   The standard atmosphere - Altitude/pressure relationship
compared with 18th and 19th Century data from Figure 2-1.

'Decompression' is used to indicate pressure reduction, regardless of starting point.

'Compression' is used to indicate raising of pressure.

'Recompression' is used to indicate raising of pressure to a previously attained level.

'Ascent' is used to denote pressure reduction, whether simulated or actually due to elevation in water or in the air. 'Descent' similarly represents actual or simulated movement in the reverse direction.

'Post-decompression' is used in a sense which is etymologically incorrect, but in accord with established practice,to denote a phase after decompression and restoration to the original ambient pressure level. It should more rationally be 'post-recompression', but prolonged usage has given the former expression a clear meaning which will be adhered to herein.

Altitude : Pressure Equivalents

Pressure and altitude tend to be used indiscriminately as synonymous and this regrettable custom will be echoed in this work, although in general elevation in feet will generally be used, with the implication that altitude is simulated unless otherwise specified.

The equivalents of altitude in millimeters of mercury (Torr) are given in Figure 2-5 and Table 2-1. They are based on an internationally accepted scale, that of the International Committee on Air Navigation. They reflect an ideal atmosphere and make no allowance for prevailing meteorological conditions other than temperature depression with ascent to the level of the 'tropopause' and constancy above that level, in the 'stratosphere'. Elevations are always measured from an assumed sea level corresponding to 760 mmHg, whereas in practice ground level may vary from this both due to physical elevation and prevailing atmospheric conditions.

3

Acute Clinical Manifestations

Introduction - Aims and Methods

The first requirement in a study of a disease or disease-complex such as decompression sickness is to define, as clearly as possible, the clinical picture. As in all medicine, diagnosis may be of necessity *post hoc* and therefore dependent upon a full knowledge of the manifestations on the part of the examiner.

Such knowledge as we have can be built up from direct observation of cases, by history-taking when circumstances make one reasonably certain of the diagnosis and by personal experience. It is in the latter category that some of the most interesting observations lie, in that curiosity and the analytical approach inculcated during medical training combine to inspire careful self-examination and often exposure beyond limits commonly set for non-medical subjects.

The descriptions following in this chapter are, unless otherwise stated, all of cases seen personally, either at the time of the decompression or subsequently, and all are the result of actual or simulated altitude exposure. They are selected from a personal series amounting to some one hundred and forty cases. In addition, documents detailing some two hundred further cases have been scrutinised. Very occasionally symptoms and signs may have been deliberately provoked in volunteers; always with their knowledge and assent.

It must be emphasised that the majority of manifestations are subjective in chalacter and therefore their analysis is dependent upon ability of the sufferer to communicate clearly and, of course, his truthfulness.

Signs and symptoms will be dealt with systematically and only particularly relevant or historically important references will be cited. Where terminological problems arise, a clear definition and selection will be attempted.

The Locomotor System

Pain in or around a joint of a limb is the commonest severe symptom of altitude decompression sickness and also of the compressed-air variety. It has the time-honoured name of 'bends'. This term has a fascinating history and it has come to mean a quite different type of condition than that to which it was most probably originally applied.

Nomenclature

During the building of the bridge across the Mississippi at St. Louis, by James Eads in 1869-1874, numerous cases of decompression sickness occurred. Woodward (1881), the historian of the project, described how "A workman walking about with a difficult step and a slight stoop was at first regarded as a fit object

C*

for jokes, and cases of paralysis and cramp soon became popularly known by the name of 'Grecian Bend'." This term refers to the fashionable affected gait which was the vogue among the young ladies of the time (Fig. 3-1). It would seem from the above description and the tottering lordotic progression of the 'bustled', tight skirted and corseted follower of fashion that the underlying condition in the caisson workers was spasticity and partial paralysis of the legs, a common enough form of disturbance under the regimen as then practised in diving and compressed air work.

Since the 1870s 'bends', as it became in an abbreviated form, has come to mean the limb pain unassociated with signs of central nervous system dysfunction. In compressed air work 'the niggles' is a common term for a lesser form of limb pain. In fact 'bends' has often been used to embrace the whole gamut of syndromes encountered in decompression sickness. The classification of Type 1 and Type 2 decompression sickness by Golding et al (1960) has, for example, led to the common use in compressed air work of the term 'Type 2 bends' to describe symptoms and signs other than simple limb pain!

In this thesis, the writer uses the term 'bends' specifically in reference to pain in or around a joint of a limb.

Characteristics

The pain of bends starts as a mild, ill-localised discomfort, dull in character and either continuous or gently fluctuating in intensity. It almost invariably increases in severity with time, and simultaneously, localisation becomes more marked. Occasionally the site of the pain will extend, radiating from the primary locus or extending along the limb proximally or distally towards another joint. Only quite exceptionally is the pain described as throbbing or lancinating. It is almost always felt to be deeply located and when at its most intense, it has been very aptly described as 'tooth-ache-like' in character.

The characteristic progression of bends is, from onset to peak intensity, of the order of 15-45 minutes, although cases of shorter and longer duration are not uncommonly encountered. Attempts to 'sit-out' bends almost invariable fail (see Chapter 7). Either the sufferer demands, and is allowed, descent, or other symptoms supervene.

As with severe pain of many types, bends can culminate in a generalised syncopal reaction, generally of the type classified by Thomas Lewis as vaso-vagal. The subject becomes aware of hot-and-cold sensations, sweating of the palms and brow often occurs, waves of nausea are common and dizziness is frequent, particularly on head-movement. The sufferer looks pale, sweaty and anxious. The pulse is 'thready' and often slow. The attack may culminate in loss of consciousness or faint, rarely with minor convulsive movements.

Location

Large-scale analyses of sites affected have been made by Stewart et al (1943) and Motley et al (1945). In general agreement with the findings of these authors are the writer's own observations of 147 cases encountered in a standardised exposure of two hours at 28,000 feet (Fig. 3-2). It can be seen that the knees and shoulders are most commonly affected, followed by the elbows, hands and wrists, ankles and feet, and the hips. The lateral distribution would appear random except for the knees. The predominence of right knees affected is quite unexplained. It would seem that sign preference on the part of observers who found themselves unable to recall the side affected when faced with form-filling would also apply to other joints such as the shoulder. This is not reflected in the analysed data. No

Grecian Bend, 1868

Fig. 3-1   The 'Grecian Bend' - a fashionable stance or gait.
(Reproduced from Cunnington, Cunnington and Beard,
"A Dictionary of English Costume", 1960, by per-
mission of the publishers A. and C. Black Ltd.)

SHOULDER AND UPPER ARM 27

29

ELBOW AND FOREARM 18

19

WRIST AND HAND 10

14

HIP 1

1

KNEE. THIGH AND LEG 43

27

ANKLE AND FOOT 7

4
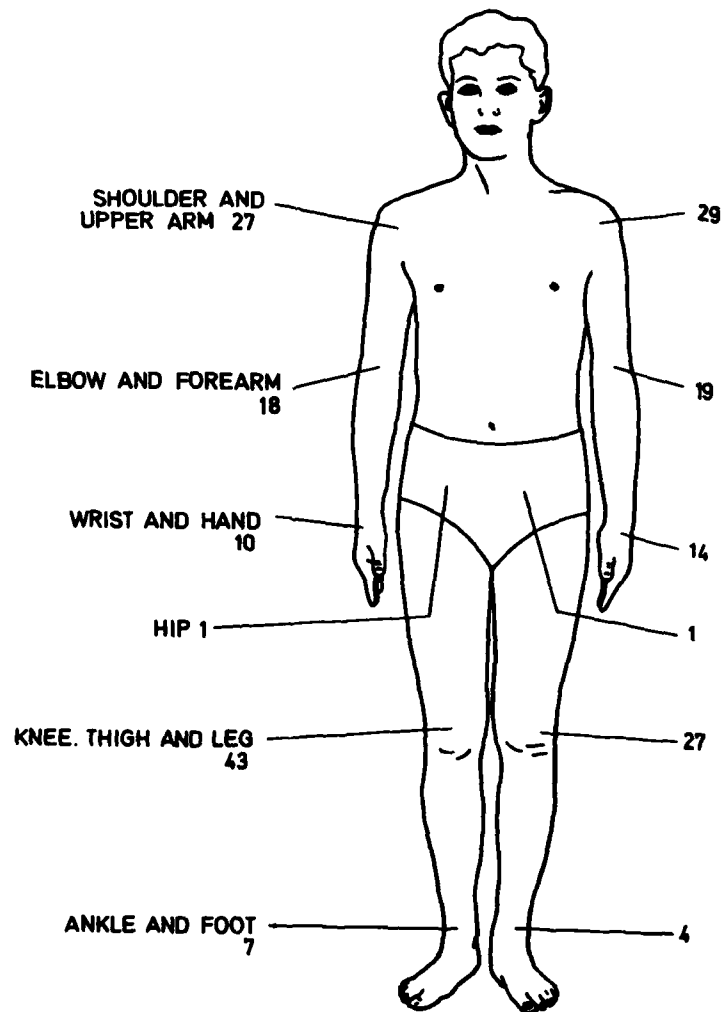
Fig. 3-2 The distribution of bends pain in 2 hour exposures to a simulated altitude of 28,000 feet.

lateral preponderancy was noted by Motley et al, except for one small sub-group.

Some individual sites have particular characteristics.   In particular bends in the shoulder is almost always first felt and, later, particularly marked in the region of the deltoid insertion.   Bends in the hands is most commonly experienced in the wrist and metacarpal regions;   bends in the knee is generally deep and often is localised to the lower part of the popliteal fossa.

Quite remarkable is the sparing of certain joints.   The writer has never seen or heard of any case of pain in any of the joints of the vertebral column, the temporomandibular joint or the sterno-clavicular joints.   Ferris and Engel (1951) state that bends occur ''... rarely in the vertebral articulations.''   No examples are cited.   In the compressed air context these joints are similarly excluded except insofar as rarely vague lumbar pains are mentioned and Corning (1890) cites occasional pain in the 'jaw articulation'.   No satisfactory explanation has been offered for the selectivity of bends for the limb joints.

Physical Signs

The site of bends pain is usually quite devoid of physical signs.   Discolouration is very rare and is probably coincidental only.   No appreciable temperature difference has been found in comparison of affected joints and their opposite counterparts. Although cramp is not an uncommon description of the pain of radiating bends, muscular spasm is not demonstrable.

Subjectively the early stage of bends is often associated with a desire to move the part, perhaps in the sense that one often attempts to work off a minor muscular or joint discomfort.   Later, when pain is very severe there is a marked contrast, the limb is almost invariably held still and it may even feel immobile.   In fact few attempts have been made, to my knowledge, to assess mobility in such cases;   understandably in view of the likelihood of syncope.   However, there is no evidence of actual mechanical restriction of joint movement and such movement rarely causes exacerbation of pain.

Multiple Bends

Pain may affect more than one joint region and it may in fact occur in all four limbs simultaneously.   A table of multiple site involvements in the series on which Figure 3-2 is based is shown below (Table 3-1).

Table 3-1.   Bends pain distribution

One limb only	More than one limb	Unspecified 'bends'	Total
116	27	3	146

Table 3-2.   Single and multiple limb bends cases

	Upper Limb			Lower Limb			All limbs
	Left	Right	Total	Left	Right	Total	
One segment	27	22	49	20	27	47	96
Two segments	6	5	11	2	5	7	18
Three segments	1	1	2	0	0	0	2

The pain in a given limb may be considered as occurring in one or more of three segments; the proximal (shoulder and upper arm, and hip and thigh); the middle (elbow and forearm, and knee and leg) and the distal (wrist and hand, and ankle and foot). Within a given single limb, multiple cases occurred as shown in Table 3-2.

In the twenty-seven cases of bends affecting more than one limb, the distribution was found to be:

Table 3-3. Single and multiple limb bends cases

Both upper limbs	10
One upper, one lower	6
Both lower limbs	5
Both upper and one lower	1
All four limbs	5

The ratio of one limb : two limbs : three limbs : four limbs can be calculated to be:

$$100 : 18 : 1 : 4$$

The ratio for multiple bends within a given limb, in terms of one segment : two segments : three segments is:

$$100 : 19 : 2$$

Because of the unfortunate discrepancy between the members of sub-divisions in the two series, direct comparison is not possible, but it would seem reasonable to deduce that the occurrence of a second bend would seem to be approximately as likely to occur in the same limb as in any other limb.

Other joint conditions

A remarkable condition was observed in a man of 20 during a prolonged exposure to an altitude of 40,000 feet, following pre-oxygenation (see Chapter 12).

Case 1

> This subject, instructed to report any abnormal sensation regardless of severity, commented that his knees "scrunched" on movement. The writer entered the decompression chamber and examined the man's knees. Both were of normal colour and temperature but clearly swollen, with prominence of the patellae and fullness to either side. On palpation marked crepitus was obvious, of a type not unlike that of massive subcutaneous and interstitial emphysema, although rather coarser. 'Patellar tap' could be elicited when the knee was fully extended. Examination of other men in the chamber revealed several other cases of lesser degree, quite symptomless. The individual referred to had clear evidence of gas accumulation in the joint-space of both knees on each of three occasions on which he was decompressed.

> Radiographs taken at altitude confirmed the clinical impression of gas within the knee joint-space (Fig. 3-3). It is remarkable that this degree of distension is painless.

> For this condition the author has proposed the term 'aeroarthrosis' (Fryer and Roxburgh, 1966).

The Respiratory System

Symptoms referable to the respiratory system are much less common than bends.

Nomenclature

The term 'chokes' is another colourful inheritance from the early days of compressed air work, although its actual origin is not documented. Hill (1912) described several cases from the literature in which asphyxia was a marked feature, but he nowhere used the term 'chokes'.

In its most dramatic form, respiratory distress can be extreme. No better description can be found than that of a Mr. Saunders, an engineer, writing in the Engineering and Mining Journal of 1891 about a visit to the Hudson River Tunnel. "... (I) was in the act of washing my boots when severe pains, increasing in intensity, caught me at a point which seemed to be at the very bottom of my windpipe. At one time I thought it was in my back, but, as a matter of fact, the pains were within my body and not at any point on the surface. They seemed to be located about the centre of the trunk. Just before entering the hospital tank (compression chamber) the pains were so severe that I was unable to breathe freely".

Symptoms

Altitude cases are rarely as dramatic as that quoted above. A typical history of an in-flight case is as follows (an actual case investigated by the writer).

Case 2

> A pilot, aged 37, was in 1958 taken to a simulated altitude of 28,000 feet in a decompression chamber. For 35 minutes he felt quite well. He then noticed a pain in his epigastrium "as though I had been punched hard in the stomach". This did not feel as though it would be relieved by eructation. The pain progressively worsened and was associated with a feeling of tightness in the chest and difficulty in taking a deep breath. An emergency descent was made and his condition almost immediately improved, but he had an intermittent cough, pain on deep inspiration and breathlessness on exertion for 24 hours after the incident.

From examination of many cases such as this and personal experience of 'chokes' on two occasions, a composite picture emerges. The initial symptom is almost invariably a sense of constriction around the lower chest, often with a tight feeling in the epigastrium, in the mid-line. Any attempt to take a deep breath is accompanied by an inspiratory 'snatch' and a soreness, often phased with respiration, soon develops deep-to and corresponding in area to the sternum. A generalised feeling of malaise with sweating palms and a sensation of cold is very common. If altitude is maintained the level at which inspiratory 'snatch' occurs becomes nearer to normal inspiration and any attempt to take in more oxygen leads to coughing. Any such coughing is followed by an attempt at deeper inspiration and so paroxysmal coughing develops. Any attempt to stay at altitude under these conditions leads to syncope, like that seen in severe bends. The local chest pains can be extremely severe and one sufferer described his feeling vividly when he stated that he felt that "if I had cut out my breast-bone and thrown it away, the pain would have gone with it".

Signs

A person suffering from chokes generally looks pale and apprehensive. Sweat is commonly seen on the brow and cyanosis has been described. Mottled cyanosis

of the chest and abdominal wall is commonly seen after descent and on two occasions where observation was possible at altitude, faint mottling of the anterior chest wall was already visible when symptoms were still very mild. No opportunity has arisen for auscultation of the chest during chokes and no description of breath sounds has been found in the literature.

The Skin

Two apparently distinct groups of skin condition resulting from decompression are generally described, one mild, the other severe. In fact, a whole range of signs and symptoms is encountered. Ferris and Engel (1951) listed prickling sensations, intracutaneous blebs, subcutaneous emphysema and mottled lesions. The writer has never seen the second condition and in the records of the Royal Air Force no such case has been found. The third, emphysema, was only once encountered by Ferris and Engel and no other description has been found of such a manifestation at altitudes below 40,000 feet. Gas is occasionally palpable in tendon sheaths (Armstrong and Borum, 1938) and large accumulations of interstitial water vapour and other gases arise during exposure to pressures of the orders of 50 mmHg (61,500 feet) or less since the vapour pressure of water at body temperature is 47 mmHg.

Nomenclature

A mild prickling or tingling sensation in the skin is commonly referred to as 'the creeps'. Although the two are sometimes confused, 'formication' should be reserved to describe a very much more severe local or general itching.

Although the Shorter Oxford Dictionary defines 'formication' as meaning "A sensation as of ants creeping over the skin" it is in medical literature generally used to denote something much more akin to biting or stinging activity of such insects. Classical descriptions of formication following injection of some of the antimonial drugs tell of persons rolling on the ground and tearing at their skin, so violent is the irritation. A French term "les puces" of indeterminate origin has commonly been used on the Continent, although whether to draw a parallel between the itching or the skin discolouration resulting from the activity of fleas and the sensations or the appearances of skin changes in decompression sickness is not entirely clear. Generally 'les puces' is assumed to correspond to formication. Finally, skin colour changes have been described as 'marbling' and the reason is clear when one sees a classical compressed air case as illustrated by Heller, Mager and von Schrötter (1900) (Fig. 3-4).

Mild Irritation

If not otherwise distracted, the majority of persons acutely exposed to altitude notice a very slight sensation of prickling in the skin, most commonly of the forearms, the thighs and the front of the torso. No visible change in the skin accompanies this sensation and it does not appear to be distributed in any relationship to the territories of cutaneous nerves.

Formication

Much less commonly very severe itching is encou...ered. A typical example of this type of case is given in the following history.

Fig. 3-3   Accumulated gas in the knee-joint of a subject at a simulated
altitude of 40,000 feet.

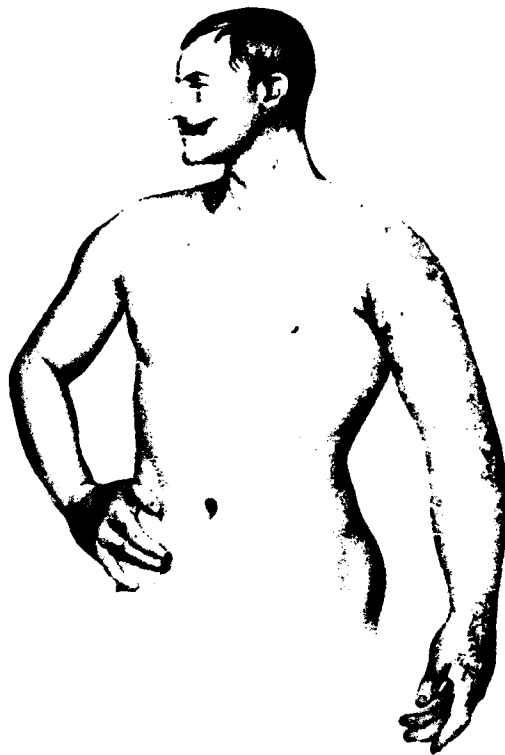Fig. 3-4 'Marbling' in a compressed-air worker.
(Reproduced from Heller, Marger and von Schrotter's
"Luftdruckerkrankungen", 1910).

Fig. 3-5   Two cases of skin mottling following altitude exposure.

Fig. 3-6   Areas of skin mottling deliberately provoked by altitude
            simulation - Case 4.
            (From a colour transparency. Affected areas outlined on
            the skin with a ball-point pen).

Case 3

A navigator, aged 31, had a history of vague discomfort and reduction in alertness at altitude on a few occasions before his first reported incident. He was then flying in a Canberra aircraft, pressurised to an equivalent of 25,000 feet. His duties entailed lying prone in the nose of the aircraft. After one hour he noticed severe irritation around the waist area and he scratched vigorously with little amelioration. After landing, 2 hours later, when undressing he noticed purple blotches in the skin of this region, not raised above the surrounding skin, but discretely tender to touch. He attributed the marks to his having scratched violently and the skin regained its normal appearance within 3 or 4 days.

Five months later he was again flying in this type of aircraft on a long navigational exercise, this time sitting in his usual seat. After an hour he experienced severe itching once more in the area of the waist, but he did not scratch himself. The irritation was so marked that at one stage he sat on his hands in order to restrain himself from scratching. The condition worsened, he felt numbness of the abdominal skin and other symptoms supervened, necessitating descent. The skin was again markedly mottled over a band from flank to flank anteriorly.

Such severe irritation is, in the writer's experience, most common in the region of the upper half of the abdomen and over the lower ribs. A few cases affecting the shoulder and upper arm have been seen and one man had very severe itching of a quite distracting intensity over a triangular area overlying the sacrum. No case has been encountered in which the head, face or distal segments of the limbs have been the site of formication.

Mottling

This appearance is, as has been described above, common over the chest in established chokes. A somewhat similar appearance is the invariable accompaniment of formication, although the degree of mottling is not seemingly related to the intensity of the irritation. Bluish-red patches of variable size appear most commonly on the trunk and over the shoulders. They may be small and discrete as in the Case three described above, fading over two to four days (Figs. 3-5a and 3-5b). Sometimes, particularly when the irritation persists, raised wheals appear. Tenderness of the underlying skin, very sharply localised and often very acute, was seen in approximately half of the cases examined personally.

Some persons present a rather different picture, which has not hitherto been differentiated. A striking example is illustrated in Figure 3-6.

Case 4

On at least five occasions in flight this aircrew officer had had similar episodes to one which was provoked deliberately in the decompression chamber. On this occasion he was decompressed to an equivalent of 29,000 feet. He developed mild bends pain in the left shoulder after 53 minutes. Nine minutes later he noticed a warm and moderately itchy sensation locally around the abdomen. On examination he had large irregular areas of reddened skin, not raised above the general level, much greater in extent than the irritation. During descent, initiated some 16 minutes later, the irritation vanished but the areas became sore, closely resembling sunburn in their combination of exquisite sensitivity to light touch and local sensation of burning. The areas of reddened skin gradually spread over the next half hour, almost coalescing until they formed a bizarre geographical appearance. They faded gradually over several days.

Desquamation is never seen in such cases. Often the smaller, more discrete patches are described as ecchymotic or petechial but in the cases seen in the active phase, in none has the skin ever failed to blanch completely under local pressure. In enquiring about the mode of regression of skin mottling, even when the patches are described as bruises, it is always found that fading takes place without any of the discolouration characteristic of the break-down of extravasated blood.

The Nervous System

Under this heading come many groups of symptoms and signs, classified according to the particular part of the nervous system apparently involved. Whether such a classification is justifiable is hard to decide, since complex afflictions are so commonly encountered that it may be justifiable to regard such cases as typical and signs of localised disturbance variants thereof, rather than to think of simple, clear-cut discrete disorders of centres and tracts, occasionally coincidentally multiple.

Nomenclature

Once again, popular terms coined by compressed air workers and divers persist in the literature and 'staggers' is a particularly vivid name for a disorder of balance. 'Spinal bend' is a more recent variant of 'bend' and although frowned upon by some as a hybrid, consideration of the origin of the term 'bends' leads one to the conclusion that this may in fact be the only sort of 'bend' corresponding to that afflicting the victims at St. Louis, Brooklyn and elsewhere in the United States in the 1870s.

Characteristics

The Special Senses - No case of disorder of the senses of smell, taste or hearing has been encountered and none has been found in the modern literature. Bizarre disorders are recorded by some of the early writers (Hill, 1912). They invariably were associated with gross motor, sensory and circulatory disturbance.

Vision - A disturbance of vision is not commonly the first sign of decompression sickness, but it is a frequent accompaniment to other symptoms. The forms of disturbed vision are varied, but a common general pattern can be discerned. Vague reduction of acuity of central vision is a striking feature. This is often associated with a blurring of the image and distortion, vividly described by two sufferers as "like looking through the sort of rippled glass used in lavatory windows". Scotomata are also frequently reported, both as defects in the visual field and as scintillating flashes or patches of light. The defect may take the form of a homonymous hemianopia and the scintillating scotomata may be organised into classical 'fortification spectra'.

A typical history of severe visual disturbance follows:

Case 5

A navigator of a larger bomber aircraft, the cabin of which developed a fault which necessitated raising the equivalent altitude within the cabin to 26,000 feet, developed mild chokes and skin irritation. Later, he noticed that his vision was blurred and that he was unable to read small numerals on instrument faces. Patches of light appeared and organised themselves into "a spiky-edged bright circle, which surrounded the blurred patch", producing an effect which he likened to a zig-zag sweep going round and round on the face of a cathode-ray tube. He also developed diplopia - a rare manifestation of decompression sickness.

Such visual disturbances are often, but by no means always accompanied by a diffuse frontal headache. Hemianopia is generally associated with a unilateral headache.

Sensory - Apart from itching, described above under the group of skin symptoms, specifically sensory disturbances are rare. They generally take the form of numbness and vague tingling of a limb which is the site of motor weakness.

Motor - Cases of weakness and paralysis, particularly affecting the lower limbs, bladder and rectum are common in the literature on 19th century caisson and diving casualties. Jaminet's book of 1871 lists many examples of this type of lesion. Fortunately, in the subatmospheric field neurological disturbances of this type are exceptionally rare. As mentioned in Chapter 2, Dr. Heim suffered from transient below-the-waist paralysis in 1938 and paralysis of one arm was reported by Behague and Garsaux in 1930.

The most severe case seen by the writer occurred during flight.

Case 6

> A non-aircrew officer, aged 48, was a passenger in an unpressurised two-seat jet aircraft on a long transit flight. Weather conditions forced the pilot to fly at 33,000 feet, and after about half an hour the passenger developed mild pain in both knees and some prickling and tingling around the lower chest. Some minutes later he noticed that his arm felt a little numb, but when told to select the emergency setting on his oxygen regulator, he managed this task with ease. He felt no better however, and the pilot suggested that he looked at his finger nails for evidence of cyanosis to support a diagnosis of hypoxia. To his horror the passenger found that he was quite incapable of moving either arm to bring his hands into his field of view. His arms remained paralysed for the rest of the flight and his legs became heavy and unresponsive when he willed them to move. By this time consciousness was becoming clouded and he had no clear recollection of the degree of motor defect of his lower limbs. During the descent he regained complete control of his limbs.

von Döbeln and Höök (1954) described a very severe neurological case. A test pilot, aged 36, was taken in a decompression chamber to a pressure equivalent to 39,000 feet. On the ascent, passing 36,000 feet, he experienced mild abdominal discomfort and this became very severe on reaching the full altitude. He then developed a "prickling, creeping feeling" along the ulnar side of both arms and into the ring and little fingers. His arms became numb and heavy, as did his legs. Within the next ten minutes, during and after the descent, he developed weakness of both arms and paralysis of both legs. Later the picture developed to reveal motor and sensory disturbances up to the level of the 7th or 8th cervical segment of the spinal cord. Recovery was slow and incomplete (Höök, 1958).

Much more complex neurological pictures can develop. For example, Adler in his review of 'Neurocirculatory Collapse at Altitude' in 1950 listed eleven types of disturbances of consciousness and psyche, twenty-one motor disorders and twenty-one types of disturbances of the skin and sensation. However, on looking at the illustrative case histories one finds that the great majority of neurological disorders were post-decompression phenomena and that disturbances at altitude were almost entirely visual, or simple numbness and weakness of the type described above. The post-descent picture which may indeed be complex, is dealt with in Chapter 7.

The Circulatory System

Apart from local circulatory disorders in the skin, described above, general vascular disorders are occasionally seen.

Nomenclature

The literature abounds with terms, apparently describing the same condition. The confusion engendered by the use of the expressions 'primary shock', 'syncope', 'syncopal reaction', 'collapse', 'fainting' and 'vaso-vagal collapse' renders classification and analysis almost impossible.

For the sake of clarity the writer introduced a system of terminology into use in the Royal Air Force which has simplified analysis without apparently restricting interpretation.

'Collapse' is used to denote a syndrome of general malaise, anxiety and diminished consciousness. The case is prefixed as 'impending' if, either spontaneously or as a result of descent, consciousness is maintained.

Cases of 'collapse' are subdivided further into 'Primary' and 'Secondary' according to the following definition.

Primary - if the first sign of adverse reaction to altitude is impending collapse.

Secondary - if the syndrome of collapse is preceded by or accompanied by bends, chokes, CNS disorder, severe skin irritation etc.

Finally, following the lead of Romano et al (1943), a group of collapse cases may be separated under the sub-heading of 'non-depressor'.

The term 'shock' is restricted entirely to the post-descent phase (see Chapter 7).

A clear picture of the sequence of events and the status of a patient may be gained by the use of such a standardised terminology. For example "impending secondary non-depressor collapse with visual disturbance" presents an image of a person suffering from visual symptoms, who develops a particular type of vaso-motor disturbance, but in whom consciousness is retained; whereas "neurocirculatory collapse and visual disturbance" might equally refer to a person who has developed the collapse before or after the vision defect, might or might not have lost consciousness and may or may not have shown peripheral vasoconstriction.

Characteristics

The common type of primary collapse is a familiar picture to any person who has been in charge of a series of decompression chamber tests. A man, hitherto behaving normally, first begins to divert his attention from whatever was engaging him such as a book or a conversation and he becomes fidgety and may look anxious. Pallor rapidly develops and if he is examined it is found that his brow and palms are cold and clammy with sweat. His fingers may appear slightly cyanosed and if his oxygen mask is momentarily removed, his lips, too, are seen to have a bluish tinge. Subjectively at this phase he may feel hot or cold, often with rapid alterations between the two. If he moves his head abruptly he may experience vertigo. Rapidly a sense of detachment develops, waves of nausea are sometimes felt, sweating becomes profuse and consciousness clouds. At this stage examination reveals an almost or complete absence of radial artery pulsation at the wrist. The pulse may

be slow or normal and is occasionally rapid; in fact there is no characteristic pulse rate. Finally, the sufferer slumps forward, unconscious. He may jactitate mildly. Cyanosis often becomes deep and apnoea or intermittent gasping supervenes. With descent recovery is generally rapid. Vomiting is quite common, as is also the development of a frontal headache.

The secondary form of collapse follows an identical pattern except where other symptoms may interfere, for example coughing may become severe and paroxysmal if the primary condition is chokes.

Non-depressor collapse is very rare. The writer has seen three cases. The first sign of disturbance is anxiety accompanied by a feeling of warmth. Palpitations may be severe. Examination shows a flushed appearance with warm, dry hands and a bounding pulse at the wrist, accelerated to a rate of 130-140/min. The sufferer feels 'wuzzy' and may, according to Romano et al (1943), actually collapse. The only cases seen personally have been treated by rapid descent before consciousness was lost.

Abdominal Pain

A rare but very ominous symptom is acute severe lower abdominal pain. This has been the principal feature of at least two of the fatal cases reported (see Chapter 8) and was a marked feature in the neurological case of von Döbeln and Höök (see above).

The two difficulties in analysing this type of symptom are: a) because of the sinister reputation of abdominal pain, immediate descent is generally ordered, usually with immediate recovery and b) because of the early descent one is never sure that the pain was a manifestation of decompression sickness rather than gut distension due to gas expansion.

One case has been seen in which the pain developed suddenly after thirteen minutes at 37,000 feet and is therefore less likely to be gas pain than if it had arisen during ascent. It disappeared completely on descent.

From the histories of published cases and the notes of others seen in the Royal Air Force it would seem that severe lower abdominal pain, continuous, with acute exacerbations and extreme nausea with an inability to vomit is a syndrome attributable to altitude exposure which may lead to the development of classical post-descent shock.

Psychological Reactions

Ferris and Engel (1951) deal at length with possible psychological reactions due to altitude exposure. In fact, none can be categorically attributed to decompression sickness rather than to the emotional aspect of the test or experiment. The writer has not seen any reaction of this type which could be attributed to anything other than pre-existing anxiety and no classical post-descent shock has supervened. The only possible psychological manifestation which may be a premonitory symptom of more serious decompression sickness is anxiety out of proportion to the situation. Thus several persons have described uneasiness, or a sensation of fear before any definite symptoms are established. This is akin to the reaction to acute internal haemorrhage or visceral perforation and may be reasonably regarded as part of the response to the intense vaso-motor activities associated with collapse, rather than a separate entity.

Association of Symptoms

Clearly it is important to investigate the frequency with which symptoms occur, both singly and in combination. It is not easy to be sure that data on which such a survey may be based are unbiased or comparable. Published surveys show strikingly different results.

Surprisingly, Fulton's book does not contain a breakdown of frequency for various symptoms in subatmospheric decompression. From the literature, the following tables may be calculated:

Table 3-4a   Percentage of symptoms associated with forced descents

	Bends	Chokes	Skin	Visual	C.N.S.	Syncope	Misc.
Motley et al (1945)	98.57	0.28	1.00	0.15	0.1		0
Russell (1943)	44	5	7	2	2	36	3
Cotes (1952)	53	14			22		10

In the writer's own analysis of a series of 4,956 exposures of 2,606 men to a standard test, the following figures emerge. One hundred and sixty-five men reported between them, 199 symptoms, and on a symptom basis only, the proportions are:

Table 3-4b   Percentage of different symptoms in 28,000 ft/2 hour test

Bends	Chokes	Skin	Visual	C.N.S.	Collapse	Misc.
73.9	4.5	7.0	2.0	1	9	2.5

In another series, tested in different circumstances with a much harsher exposure the figures, based on 65 symptoms, yield the following analysis:

Table 3-4c   Percentage of different symptoms in 37,000 and 25,000/37,000 ft tests

Bends	Chokes	Skin	Visual	C.N.S.	Collapse	Misc.
56.5	6.5	1.6	4.8	0	25.8	4.8

It can be gathered from these data (Tables 3-4a, b and c) that symptom proportions vary from series to series. Factors which might possibly explain these discrepancies are discussed in Chapters 5 and 6. Meanwhile it may be safely stated that bends pain is by far the commonest manifestation of note. When forced descents are considered, the incidence is very different, syncope increasing greatly. This is an indication of a proportion of bends cases developing secondary collapse, this complication always being regarded as an indication for forced descent.

The literature contains many statements to the effect that one type of symptom or sign is often associated with another. There is no published statistical evidence for such statements. It is probably not justifiable to make detailed analyses of small series but the clinical impressions that chokes is often accompanied by skin

changes and impending collapse, that abdominal pain is commonly associated with collapse etc. are worth recording. The relative frequency of various symptoms as isolated events or as parts of complexes is set out in Table 3-5, based on the 199 symptoms reported in the 4,956 exposures to 28,000 feet.

Table 3-5   Relative frequencies of single and multiple symptoms.

	Bends	Chokes	Skin	Visual and C.N.S.	Collapse
Isolated	77.6	0.6	4.3	1.8	2.4
Complex	11.5	4.2	4.2	1.8	10.3

It will be noted that the ranks and columns do not sum to 100 : this is because a case may appear twice, e.g. a case of bends and collapse will appear as a complicated bend and as a complicated (i.e. secondary) collapse (lower right). The picture that emerges from this table is that bends is often simple, whereas chokes and collapse are rarely isolated occurrences. CNS disturbances and skin signs and symptoms on the other hand, appear as commonly as isolated manifestations as they do as parts of symptom complexes.

Although it is not intended to carry out detailed parallel studies of compressed air and diving casualties in this context, it is of interest to note the following relative incidences derived from the literature on diving cases.

Table 3-6   Frequency of symptoms in divers.

Author	Bends	Chokes	Skin	Visual	C.N.S.	Collapse	Misc.
Slark (1962)	71	0	Not listed	1.5	15.9	9.2	2.4
Rivera* (1964)	45.9	1.0	7.5	3.4	32.8	5.4	4.0

* Note: It is not easy to be dogmatic about the allocation of some classes of symptoms in the original report, such as "muscular weakness", "muscular twitching", "unconsciousness" etc. The main groupings are felt, however, to be reasonably accurate as a basis for comparison with Table 3-4.

In compressed air work the predominant symptoms are bends. Few detailed analyses have been carried out. Kleinfeld and Wilson (1956) gave the following figures:

Table 3-7   Frequency of symptoms in compressed air workers.

Bends	Chokes	C.N.S.	"Staggers"	Abdominal Cramps
90%	1.0%	1.3%	3.6%	4%

Conclusions

The manifestations resulting from exposure to altitude which are collectively referred to as decompression sickness are protean. There are a number of reasonably clear-cut symptoms and signs, but they may occur in numerous combinations and sequences. In the majority of cases diagnosis would appear to be possible on a basis of established clinical descriptions. In a few cases, diagnosis must be by exclusion, on the bases of the definition of decompression sickness as "those signs and symptoms associated with reduction of atmospheric pressure .... not

apparently due to the expansion of trapped or enclosed gas and not primarily due to oxygen lack" (Chapter 2) or by observation of the development of classical post-decompression complications (Chapter 7).

Mechanisms Underlying Clinical Manifestations

Introduction

It is always to be hoped when investigating a clinical syndrome that the mechanism might be discovered, in order that the interactions between the causative agent and the host might be better understood.   It is particularly important that such investigations are successful if the causative agent is not susceptible to direct attack and, consequently, symptomatic relief is the mainstay of treatment.

The literature on decompression sickness is vast, amounting to several thousands of references, and yet the explanation of symptoms and signs is far from established.   This is no place to delve into the enormous number of theoretical papers on the biophysics of nitrogen diffusion or bubble mechanics;   can one find either a single explanation, or a series of individual explanations for the occurrence of the numerous conditions described in Chapter 3?

The only common links between symptoms appear to be:

(a)   their initiation under similar environmental conditions

(b)   their prevention by a single manoeuvre - the removal of nitrogen from the body.

Methods

There are many approaches other than that of direct observation.   If one cannot see a cause, naked-eye or with the aid of the microscope or X-rays, one can perhaps draw conclusions by analogy.   What other agents can cause the same symptoms?   One may also find a clue to the solution if a remedy is found and its mode of action is understood.   It is interesting, but disappointing, to apply these approaches to the study of individual manifestations of decompression sickness.

Bends

Can a mechanism be deduced from the vast amount of accumulated knowledge about the common 'bend'?   Armstrong (1939) and others assumed that bubbles in the arterial tree lodging in peripheral vessels caused the pain of bends; this is implicit in Armstrong's name for the condition 'aeroembolism'.   Ferris and Engel (1951) listed a number of objections to this theory, including the absence of skin changes suggestive of blood flow disturbance, the effectiveness of local pressure in relieving pain even when the pressure may have aggravated the circulatory obstruction, the lack of similarity to the pain of ischaemia, the recurrence of pain in the same site on re-ascent and, most cogent of all, the theoretical improbability of arterial supersaturation with nitrogen, the blood having just had an opportunity to lose excess nitrogen during passage through the pulmonary capillaries.

If bends pain is not due to embolism, what other mechanisms might explain the symptoms? Bubbles in sensory nerves or in nutrient arteries of nerves have been suggested. Some authorities suggest that irritation may originate within or adjacent to the dorsal roots themselves.

Against such theories is the proven effectiveness of local pressure. Early studies on compressed air workers suggested that local pressure and friction might help. Fraser and Waters (1942) showed simply but elegantly that local pressure relieved bends. Subjects with pain in the lower limb at 35,000 feet lowered themselves into a tank of warm water. Pain was almost always relieved when the water reached mid-chest level. Bends in the wrist were relieved by immersion of the arm to shoulder level. Pain recurred on emergence from the water. The relieving pressure can be readily calculated, each foot of water exerting approximately 25 mmHg; thus leg pain was relieved by 75 to 100 mmHg and wrist pain by about 50 mmHg. These pressures are, in turn, equivalent to descent to 25,000 to 27,000 feet for the lower limb and 30,000 feet for the upper. It is well known that 'whole body descent' of this degree is generally effective; that local pressure is equally so is indicative that proximal lesions, say of nerve roots, are unlikely to be present. Pask (1942) in two experiments demonstrated a similar effect by use of a rubber bladder over the leg, inflation to 80 mmHg relieved bends at 32,500 feet. Here pressure could be uniformly applied and the gradient effect of water eliminated. Anthony et al (1943) and Lansing (1944) made similar observations with local sphygmomanometer cuffs and Webb et al (1944) used mercury troughs with identical results.

The writer has observed that local pressure within the sleeve of a pressure suit relieves bends. In a particular type of suit (Fryer, 1966) the pressure over the limbs can be dumped whilst thoracic counter-pressure maintained. Whilst suffering from mild shoulder bends it was quite clear that at 45,000 feet deflation of the sleeve caused recrudescence of bends, whereas re-inflation eased the pain immediately.

Gas within the joint space has often been claimed in the past to be a cause of bends pain. The observation of large volumes of gas in painless joints has been made by Evelyn (1943), Webb et al (1944) and Bromley and Harvey (1944), and further evidence on this point is shown in Figure 3-3. Ferris and Engel (1951) reviewing the evidence of Webb and others quote a correlation between interstitial streaking on X-rays and symptoms. These appearances are certainly present in some of their films but caution must be exercised in their interpretation in view of the demonstration by Bromley and Harvey that such appearances are common in X-rays in normal subjects not exposed to altitude at all.

A novel and unpublished theory was put forward by Matthews in 1939. He pointed out that atmospheric pressure normally plays an important role in maintaining contact of joint surfaces. He calculated that to separate the knee joint at sea level might require some 150 lb. of tension, whereas at 40,000 feet this would be reduced to 20 lb. He suggested investigation into the possibility that abnormally readily produced joint surface separation might be important. In fact, in 1941 it was reported from Farnborough that traction actually eased some bends pains. This theory also would not seem to be compatible with bends pain following decompression to 1 atmosphere from higher pressure.

The most generally accepted explanation of bends is that put forward by Inman and Saunders (1944) who showed that local injection of physiological saline at pressures of the order of 25-30 mmHg into the sub-periosteal plane, into ligaments, joint capsules, tendons, fascia and even muscles caused pain closely analogous to that of bends. They proposed the possibility that extravascular bubbles in these tissues could be responsible for the pain.

A possibility which has not be investigated, but which is not inherently improbable, is that bubble obstruction of venous outflow from the medulla of a long bone may be a cause of pain by leading to local sinus distension and stagnation. The anatomical features of large medullary venous channels draining by way of narrow cortical passages through compact bone lend support to such a concept. It would also perhaps explain why pain does not occur in other bony sites, since the vascular foramina in bones such as the vertebrae would appear to be much larger. The periostial and ligamentous origin theory does not explain the sparing of the spinal column and other bones. Perhaps there is some other cause for the apparent association between bends pain and the existence of thick, dense cortical bone. It is of interest in this context that the lesions of caisson disease of bone (ischaemic necrosis) are limited to the bones of the limbs, as are the pains of bends. Surely the coincidence of the sites most commonly affected by the two conditions is unlikely to be due to chance. It is surprising that so far as is known, attention has not hitherto been drawn to this fact.

The observation that local pressure eases the pain of bends might appear difficult to reconcile with this theory. However, obstruction of venous return from the limb should be reflected by a rapid equilibration of venous pressure across the bone. If the local pressure is raised above arterial systolic pressure, one might presume that both the absence of a driving pressure and the transmitted compressing force on the bubble might reduce the local tension on pain-producing nerve endings at the bubble site.

Chokes

The aetiology of chokes has been the subject of much speculation. It remains indefinite.

Early in the history of altitude studies it was suggested that the symptoms known as chokes were due to pulmonary gaseous embolism, (Armstrong, 1939). Such an aetiology was vehemently denied by Ferris and Engel in 1951, on seemingly sound reasoning. They cited the absence of any chokes-like symptoms in a person accidentally given 300 ml. of air intravenously, they found no clinical or radiographic evidence of congestion or dilatation of pulmonary vessels, they found no ECG changes indicative of cardiac strain and they noted the recurrence of chokes on re-ascent, in spite of the probability that any intravascular bubbles would have been expected to have become small enough to pass through the pulmonary bed under these circumstances.

They quote interesting unpublished observations on attempted induction of local bubble formation and release. Similar experiments were unwittingly carried out by the writer and a colleague in 1952, with similar results. In fact the conditions were even more extreme than those in the experiments cited by Ferris and Engel, and therefore their outcome augments rather than merely confirms the then unknown similar experiments.

A sphygmomanometer cuff was placed on the upper arm and inflated to a pressure of the order of 200 mmHg, sufficient to occlude all circulation. The subject was then decompressed to 40,000 feet at a rate of some 4,000 feet/minute, the cuff differential pressure relative to ambient being maintained. Vigorous repeated contraction of the forearm was carried out by clenching the fist and flexing the wrist until ischaemic pain prevented further effort. According to the animal experiments and theorisation of Harvey (1951) and Blinks, Twitty and Whitaker (1951) the conditions in the forearm should have been highly conducive to bubble formation and growth. There was complete ground-level gas saturation of blood and tissues, CO_2 accumulation, lactic acid release, shear forces within the muscles and hypoxaemia.

No bends pain was apparent, but in the presence of severe ischaemic pain it might well have been masked. Abrupt release of the cuff should have led to release into the circulation of bubbles, passing *en masse* to the right heart and thence to the pulmonary filter. Chokes-like sensations were completely absent in both subjects in each of two experiments. Chest X-rays taken at altitude within seconds of the release showed no sign of pulmonary or cardiac disturbance.

What of the evidence from accidental venous gas embolism? Ferris and Engel dismissed evidence rather lightly and quoted but a single case. Most of the many cases of venous air embolism recorded in the literature have either been immediately catastrophic (e.g. Tureen and Devine, 1936; Rangell, 1942; Cohen et al, 1951; Vigouroux and Nivelleau, 1960; Geraud et al, 1963; Bauer et al, 1965) or have occurred during general anaesthesia. (Whitby, 1964, reviewed the early literature; other typical cases are reported by Cammermeyer and Adams, 1954; Hunter, 1962 and Emery, 1962).

In distinct contrast, the slow, controlled admission of oxygen into the venous side of the circulation was once practised as a supposedly effective treatment for shock. In fact, there was good evidence available that such therapy effectively reduced the arterial pO_2 (Grodins, Ivy and Adler, 1943), but some surgeons persisted in its use. Jacóbi et al (1946) for instance, would give as much as 600 ml/hr for thirty hours to a patient. Sanders and Isoe (1947) reported on their observations on six human cases, four of whom were conscious. The first complained of "... a sensation of pressure in the lower chest, cough, restlessness and profuse perspiration"; the second reported "... difficulty in breathing, cough, yawning, feeling of faintness, restlessness and profuse perspiration"; the third "... suddenly commenced to cough, perspired very profusely and was obviously very apprehensive. He also complained of a feeling of compression about his lower chest"; the fourth "... suddenly complained of precordial pain". In all, symptoms were associated with high rates of infusion (9.3, 7.2, 10.0 and 6.0 ml/minute respectively) and all improved within minutes of discontinuation of the administration of the oxygen. Sanders and Isoe commented on the similarity of the symptoms to those of aviator's chokes. Their work does not seem to have come to the attention of Ferris and Engel.

Can the disputing evidence be resolved? The cuff occlusion experiments may have been misleading. There is no proof that bubbles existed in the limb prior to cuff release. The forearm and half the upper arm of a man amount to approximately 7% of the total body mass. The body contains, at sea level, approximately 1 litre of nitrogen in solution. How much would be released within the arm? The pressure range of the decompression was 1 to 0.2 atmospheres absolute and as circulation was occluded and no allowance need therefore be made for loss of N_2 via venous return, the total nitrogen available for release would amount to:

$$\frac{0.07 \times 1,000 \times 1}{0.2} = 350 \text{ ml at } 40,000 \text{ feet}$$

Admittedly other gases would diffuse into bubbles, but on the other hand, in the available time diffusion from tissues remote from the major veins cannot have been complete. Thus we are left with the probability that something of the order of 200 - 400 ml of gas bubbles might have been released. The fact that symptoms were not produced would seem hard to reconcile with the theory of gaseous embolism causing the symptoms of chokes.

Apart from subjective reports, what evidence is there of a response to pulmonary embolism other than simple mechanical obstruction? The literature is vast and largely contradictory. Controversy is still keen on the question of active or passive pulmonary artery hypertension following microembolism, whether due to sounds or

gas. On the respiratory mechanics response, however, there is more harmony between authors. Shaw Dunn, in 1920, found evidence of bronchospasm and vagus-mediated tachypnoea following starch embolism in goats. Since then similar effects have been shown to result from embolism by all manner of particulate matter and Singh (1936) showed a response to gaseous embolism. The mechanism has been particularly studied by Nadel, Colebatch and Olsen (1964) using Barium Sulphate particles in cats and by Thomas et al (1964) who worked with autologous thrombi in dogs. These workers claimed a dominant role for histamine and 5-hydroxy-tryptamine (5HT) respectively. In both species and with the two types of embolic material the response was one of bronchial and alveolar duct constriction with a fall in pulmonary compliance and a rise in airway resistance. Is this relevant to gaseous embolism in man?

The writer has made an exploratory study on dogs, anaesthetised, but breathing spontaneously. In a preliminary report (Fryer, 1965) he was able to describe that with air dosages of considerably less than the lethal minimum the response in that preparation was rapid shallow breathing with a fall in pulmonary compliance and a rise in resistance. A typical response is shown in Figure 4-1. The tachypnoea and reduction in tidal volume are both abolished for all but massive doses by vago-tomy, but the air passage constriction is not altered by this procedure.

Evidence for a humoral transmitter for the effect of embolism is based largely on Colebatch and de Kock's experiments reported in 1963, in which they showed a diminution in lung histamine content after Barium Sulphate embolism and a closely analogous responses to histamine and to microemboli. Colebatch (1964) believes that the very dramatic type of response which he and his colleagues have observed is specific to particles of a limited size range, about 15μ .

Montanari and Giaroli (1962) reached the conclusion that 5HT, or 5HT-like material was released from rabbit lungs by gaseous embolism because they found reduced levels in lung extracts after such an instance.

There are virtually no observations on man which can relate his response to that of animals. Bronchospasm as a clinical entity is relatively common in severe de-compression sickness in caisson workers (Bennison, Catton and Fryer, 1965) and the picture of fully developed chokes is very similar. Parsons (1959) attempted to measure vital capacity and expiratory spirograms in cases of forced descent during altitude decompression tests. Three of thirty with bends sufficiently severe to warrant forced descent and five with neurological, respiratory or syncopal manifestations, showed a reduction of vital capacity. This was almost certainly due to limitation of inspiration of a chokes-like nature. Four of the eight subjects in fact had respiratory symptoms and it is the writer's experience that following descent from altitude it is quite common to note slight inspiratory 'snatch' on attempting to take a deep breath, even in the absence of any symptoms at rest. One subject only showed a diminished rate of forced expiration.

Ferris and Engel were in favour of local bubble formation in the mucosa of the res-piratory tract as a cause of chokes. They extended this concept, based almost entirely on a similarity to irritative conditions of the respiratory passages, to in-clude "throat chokes" for a pharyngeal form. Parsons accepted the opinion of Ferris and Engel unquestioningly and further extended the concept to talk of in-flammation and oedema, accentuation of the stretch reflex and alteration of alveo-lar wall diffusing capacity and blood flow. He advanced no evidence to support such theories, other than the presence of central cyanosis in three subjects breathing air at ground level and the clinical picture of chokes.
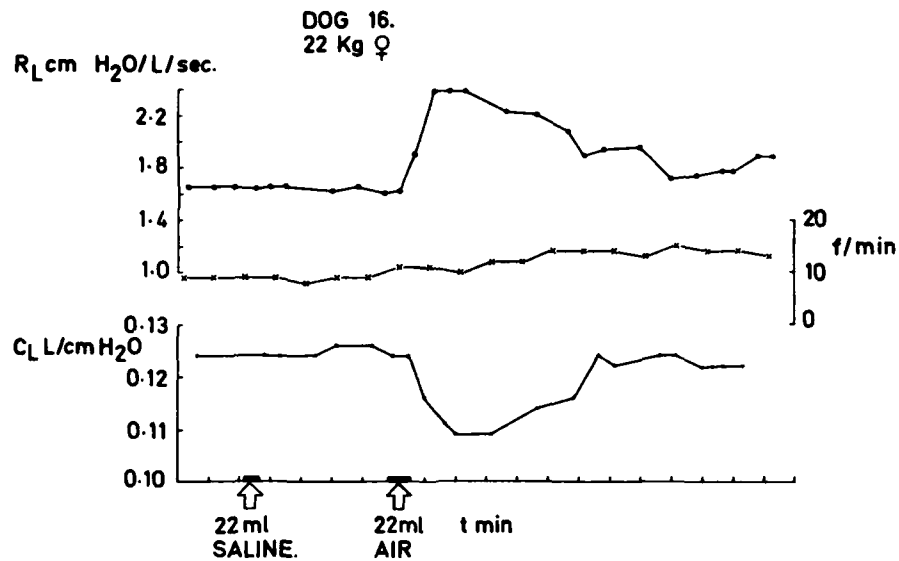
Fig. 4-1   The respiratory response of an anaesthetised, spontaneously-
breathing dog to introduction of 1 ml air/kg. into the pulmonary
artery.   Records from above: below;   resistance, respiratory
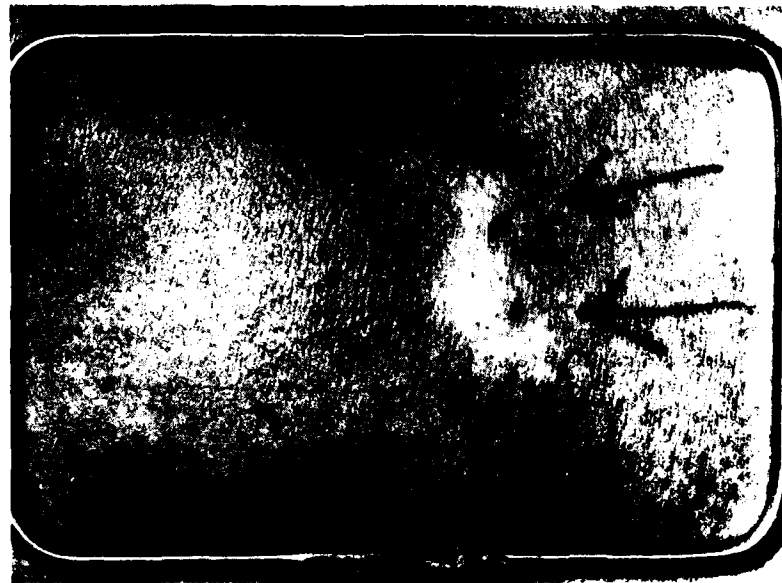rate, and pulmonary compliance.

Fig. 4-2   Local blanching produced in an area of mottling in Case 4 by in-
jection of 1:10,000 Adrenaline solution (sites indicated by arrows).

Skin Changes

No fully satisfactory explanation has been established for the full range of skin manifestations which have been observed.

Formication

Classical descriptions of formication are found in the literature on trypanosoma-cidal drugs. Of stilbamidine, Kirk and Henry (1944) stated that "In our experience the most common immediate disturbance was generalised formication described as "niml, niml" (ants, ants) by the Sudanese patients ......". Pentamidine was described by Lourie (1942) as often causing itching, sometimes precipitant and so severe as to lead to "... grotesque antics, trying to scratch every part of his body simultaneously". Such reactions are generally attributed to histamine and allied substances such as the active polypeptides being released locally. Lecomte (1956) described the response of man to intravenous histamine liberator 1935b. A small dose, 0.1 mg/kg caused "needling" after 2 - 3 minutes, intolerable pruritus of the face and palms, and flushing. A heavier dosage, 0.3 mg/kg caused more severe pruritus, spreading to the trunk, tachycardia and headache and erythema lasting 10-15 minutes. The largest dose, 0.5 mg/kg, caused a massive reaction, including urticaria and sometimes nausea and vomiting.

The sparing of the face and the absence of pronounced tachycardia would seem to indicate that in decompression sickness such a release of histamine could not be general, but rather local, i.e. the affected areas. To what might one attribute local histamine release?

Experimental investigations of skin changes have rarely been recorded. Rashbass in 1957 reported on some eminently simple experiments on the itching commonly arising in divers during ascent from real or simulated depth. He showed that skin irritation did not arise if the limb or the whole body was immersed in water during compression and soak at depth, but removed during ascent. He concluded that the source of irritation was nitrogen dissolved in the skin directly and not carried there by the blood stream.

Mottling

Local skin colour changes very similar to those of mottling have been clearly described as a response to experimental arterial gas embolism in man (Duff, Greenfield and Whelan, 1953) and also in accidental gaseous embolism of arteries (Durant et al, 1949). It is of great interest, however, that the skin colour changes so caused were never associated with pain or itching and that they were of relatively short persistance compared with the mottling of decompression sickness.

The distribution of mottling in many severe cases, over the upper chest and upper arms, has led to the suggestion that since fat embolism has been demonstrated histologically in decompression fatalities and fat embolism causes a 'rash' of this distribution (Sevitt, 1962), arteriolar obstruction by fat globules might be the cause. This theory is not tenable. These lesions resulting from fat emboli are undoubtedly petechial. There has been no convincing evidence of extravasation in compressed air cases (Griffiths, personal communication) or in altitude cases seen by the writer. Also whenever other evidence of fat embolism, such as fat in urine, fat in the sputum or retinal fat emboli has been sought, findings have always proved negative.

Two investigations have been carried out on the case of mottling illustrated in Figure 3-6. It will be recalled that this subject (Case 4) was one who could be predicted to produce large reddened sore areas when decompressed to altitude.

64

When induced to develop this condition in the decompression chamber a patch on the abdominal wall was selected and at two marked sites approximately 0.1 ml of 1:10, 000 solution of adrenaline was injected intradermally. The response was rapid and unequivocal blanching, spreading over an area of approximately 2 cm diameter around each site. This is taken to indicate that blood is definitely still intravascular in these reddened patches and that the capillary and arteriolar vessels retain their responsiveness to adrenaline (Fig. 4-2).

The second experiment, on the same subject, was to compress him to a pressure greater than that prevailing at sea level. He was accordingly put into the compression chamber at the Institute of Aviation Medicine, Farnborough, and the presure was raised to 4 atmospheres absolute. At this depth he noted quite spontaneously that the irritation and tenderness had vanished and it was clear to the writer, who accompanied him, that the previously delineated reddened patches were fading in intensity and diminishing in size quite rapidly (a noticeable change being present after two minutes). The lesion darkened again and became more tender, though not as markedly so as before, after return to sea level and fading proceeded at a very much slower pace.

This is put forward as evidence of bubbles as the underlying lesion in this type of skin condition. It tells us nothing of the site of the bubbles nor of the mode whereby they produce vasodilatation,whether it be humoral or nerve-mediated. The work of Duff, Greenfield and Whelan (1954) and many others since then has shown good evidence that the vasodilatation due to arterial gas embolism is not a nerve-fibre conducted reflex, either axon or trans-synaptic.

The Nervous System

Ferris and Engel (1951) were most explicit in their studies of these manifestations of decompression sickness. They report on EEG changes in the form of slow-waves in the occipital region contralateral to the visual defect. Engel et al (1944) studied forty-six occurrences of scotomata on seventeen susceptible subjects. All also had other manifestations of decompression sickness.

The general opinion regarding the causation of any of the neurological pictures - visual, motor or sensory - seems to incline towards gaseous embolism and spasm. As described above, the recorded clinical cases of accidental gaseous embolism are almost entirely catastrophic or associated with general anaesthesia and there is therefore little to be learned from this source. It would appear to be logical to suggest that if bubbles are the underlying agents of decompression sickness, then focal embolism and obstruction might account for the bizarre neurological findings in acute cases, but the evidence from limb vessels would seem to make spasm most improbable.

The whole question of the role of systemic gaseous embolism in decompression sickness is deferred until Chapter 9.

Collapse

The major attempt at the analysis of all types of collapse at altitude and following descent was made by Adler in 1950. His excellent review cannot be improved upon for thoroughness. He was unable, however, to offer a satisfactory explanation for collapse when it occurred.

In the case of secondary collapse as defined by the writer in the preceding chapter, pain and apprehension could well be sufficiently intense to account for a vaso-vagal type of collapse. It is of interest in this context to note that Mahady (1943)

observed low pulse rates in cases of severe bends and chokes, even to the extent of one case with an ECG-verified cardiac rate of 34 per minute. This implies strong vagal activity.

The primary collapse as defined in Chapter 3 is very hard to explain. Adler, whose series included about 11% of this type of reaction, could find no satisfactory theory. Vasospasm has often been invoked, particularly since Knisely claimed to observe vasoconstriction in conjunctival vessels at altitude. It is very bold to attempt to infer changes in vessels in any other part of the body from such an isolated observation. Presumably the proponents of the spasm theory suppose that cerebral vasoconstriction could cause ischaemia. The general thesis would appear to be that bubbles lodge somewhere in the brain, causing a vasomotor reaction, but there is no evidence either for or against such a concept.

For the rare non-depressor type of collapse case it is tempting to postulate release of some potent vasoactive hormone, as occurs for example in cases of carcinoid tumour. There is no evidence to support such a theory and no case of subsequent detection of such a tumour has been reported, including those seen and followed up by the writer.

Abdominal Pain

Gas expansion is a common cause of abdominal pain at altitude, particularly in the inexperienced (Ferris and Engel, 1951). The rare severe abdominal pain, usually associated with very grave post-descent disorders (see Chapters 7 and 8) has no explanation. It would appear to be different in character and presumably in aetiology from so-called 'gas pain'.

Conclusions

This chapter has been difficult to compile and has proved depressingly inconclusive. It is indeed sad that no firm explanation can be put forward for any of the manifestations of decompression sickness and it is quite impossible to find a unifying theory which would explain all the symptoms and signs, other than a vague general unsupported theory of disseminated gaseous embolism. Decompression sickness is in a class with many of the mild exanthematous diseases; cases are almost invariably non-fatal and therefore inaccessible to the pathologist and when patients succumb their pathology is confused by complications. The fact that one cannot safely maintain at altitude an established case hinders or prevents almost any form of investigation. The virtual absence of an analogous condition in most animals prevents deductions being made from such material and the finding of bubbles in animals such as dogs under anaesthesia with intravascular catheters does not necessarily imply a similar status in a normal human subject.

5

Environmental Factors

Introduction

In the preceding chapters an attempt has been made to define and illustrate the
various acute manifestations of decompression sickness. On the whole, the
condition as it affects aviators is not unlike the 'caisson disease' of compressed
air workers and the picture of 'divers' bends'. The principal differences have
been considered by Haymaker and Johnston (1955) and by Gribble (1960).

The main concern of those working in these hyperbaric fields is the prevention
of decompression sickness by the control ascent rates and 'staging' (step-wise
pressure reduction). In aviation in the early days of military altitude flying on
a large scale, the pre-occupation was in selection of those best suited to tolerate
a condition which was operationally essential. This led to the vast expenditure
of time and man-power on the strictly practical selection process. Motley,
Chinn and Odell (1945) for example, could call upon data from 68,422 trainees.
Much effort was also put into the mathematical analysis of this and more experi-
mental data (Nims, 1951; Bateman, 1951) and fundamental biophysical studies
on bubble formation.

At the same time, technical progress was being made in the development of
pressurised cabins for aircraft (Lovelace and Gagge, 1946) and medical re-
commendations were required for the selection of the optimal compromise
between a high pressure differential for physiological protection and a low
differential desirable to reduce the hazards should cabin failure occur.

Now, with increasing aircraft ceilings and more reliable cabins the emphasis
has again shifted, to the physiology of the occupants of cabins the altitude
equivalent of which was decided upon many years ago. For example, the 8,000
ft cabin generally assumed to be without blame has been shown to lead to
unequivocal detriment in performance of a simple but accurately assessable
psychomotor task (Denison and Ledwith, 1966). Similarly, as will be illus-
trated below, the 25,000 ft equivalent of the low-pressure-differential military
cabin is not as safe from the point of view of decompression sickness avoidance
as had been hoped when the level was selected.

To be of service to the designers and operators of aircraft, the aviation physio-
logist should do his utmost to ascertain the fullest possible information of the
factors governing the occurrence of decompression sickness. Thus armed
he should be prepared to advise on the three related problems of:

1)   What cabin conditions will provide an absolute protection against decom-
      pression sickness, or will limit the occurrence to a given frequency?

2)   What incidence of decompression sickness will be expected to occur in
     given operating circumstances?

3)   What factors will influence the occurrence of symptoms under given
     environmental conditions?

The currently available literature provides many clues as to the answers to
these questions, but there have been many gaps and not a few invalid assump-
tions, and there does not appear to exist an authoritative and scientific guide.
It is with this in mind that the writer has attempted in this and the succeeding
chapter to make the maximum use of the data obtained from clinical observa-
tion and tests of aircrew, and from critical analysis of the scattered published
data of others.   Analyses are much more critically dependent upon the nature
of the raw data than is generally appreciated.   Time and time again in this
field one finds evidence of over-extrapolation from unworthy data.   For example,
one author will combine data from quite different populations without realising
(or acknowledging) the relevance of the composition of the groups.   Another will
take the process one step further and manipulate the summed data from such
various sources and calculate, to an unwarranted degree of pseudoaccuracy,
the arithmetic means of such figures without allowance for the size and inhomo-
geneity of the population.

The Sources

Where specific references are not quoted, the data in this chapter and Chapter 6
are the result of the writer's own analysis of records of tests of aircrew and other
subjects.   They fall into three categories; a series of over fifty individuals seen
interviewed and examined as a result of some past incident, many of them sub-
sequently decompressed as part of their investigation; some ninety cases witnessed
during routine and special tests carried out at the Institute of Aviation Medicine
under the writer's direct supervision; and almost 200 cases analysed by full
scrutiny of records, over 10,000 in total.   The major part of the analysis is
concerned with a particular test which was largely designed by the writer and the
documentation and standardisation of the reporting was based upon the writer's
recommendations to the Air Ministry.

The Classification

It is soon apparent when one attempts analysis of data on decompression phenomena
that the information derived is not readily divisible into categories.   The prime
analysis is that of the behaviour of a group, the secondary is that of the individual
components of that group; it becomes obvious that it is impossible to deal with
group response without reference to individuals and vice versa.   However, an
attempt is made to categorize data into two broad groups.   (a) Environmental
factors are those features of the exposure to which all members of the group
are subject.   They therefore dictate the overall population response and enable
one, it is hoped, to forecast the behaviour of a group of comparable composition.
(b) Individual factors (Chapter 6) are those aspects of the group components,
whether individuals or sub-groups, which will influence the total response to a
given environment.   Only from analysis of the influence of such factors can
one gain the necessary background on which to base judgment of comparability
of populations in assessing environmental factors.

The Environment

Those features of an altitude exposure which may be anticipated to affect the
occurrence of decompression sickness are,in logical sequence:

a) The initial (or base) altitude.
b) The rate of pressure reduction.
c) The final altitude.
d) The period of exposure.
e) The prevailing thermal conditions.

Because the first is almost always within very narrow limits and, as will be
seen, the second is relatively insignificant, these factors will be dealt with in
a more convenient sequence in this chapter.

The Altitude of Exposure

As will have been seen in Chapter 2, not surprisingly, the early discoveries in
the response of man to altitude were associated with exploratory single or small
group experiments in which the attainment of maximum altitude was generally the
aim.   Thus Armstrong stated in 1939 that symptoms were seldom noted up to
30,000 feet, that they could affect susceptible individuals at 32,500 feet, that
symptoms may or may not arise at 35,000 feet and that they were very likely
at 37,500 feet.   Subsequent work, effectively summarised in Fulton (1951)
added much needed precision to these statements, but it is surprising that no
simple authoritative table or graph of altitude/susceptibility was included.

Nims (1951) plotted data from many sources (Fig. 5-1) and deduced that there was
a linear inverse relationship between barometric pressure and incidence, and that
this relationship was remarkably constant (i.e. the slope was the same).   Con-
sideration of the origins of the data led Nims to conclude that the slope would be
influenced by the period of exposure and the activity of subjects (see Chapter 6)
but that group composition had little influence.

Figure 5-1 may have satisfied Nims so far as the confirmation of his mathematical
reasoning was concerned, but it is of little practical value to the designer or
operator of aircraft.   For example, posing the simple question - What incidence
of decompression sickness should be expected at 35,000 feet, would yield per-
centages of 12, 32, 41, 53 and 90 according to the line chosen?   Conversely,
the altitude at which a zero incidence could be anticipated varies similarly,
different series yielding safe heights of 23,250, 27,000, 28,500 and 32,000 feet.

Bateman (1951) also attempted a mathematical rationalisation of the data of others,
extending his work to cover high and low pressures, desaturation procedures and
time of exposure (Fig. 5-2).   From his graphs one cannot obtain incidence, but
thresholds.   The plot, with which he was satisfied to the extent of stating that
it "...... undoubtedly gives a fairly accurate statement of the facts", would
suggest that the critical altitude below which symptoms would "never arise"
would be 34,000 feet for a one hour exposure and 26,000 feet for a five hour
period.   How does this compare with Nims?   The latter's analysis, ignoring
the time factor, would suggest an incidence of up to 20% at 26,000 feet and
anything between 10% and 85% at 34,000 feet !

The writer has selected from the recorded analyses of R.A.F. decompression
tests at three altitude levels and from the U.S. literature, a series of exposures
which have in common:

a) age and physical status, ranges corresponding to a relatively unselected
    aircrew population (in contrast to laboratory personnel or prospective
    aircrew candidates).

ALTITUDE ft ×10⁻³

INCIDENCE Ns/N

PRESSURE mm Hg.
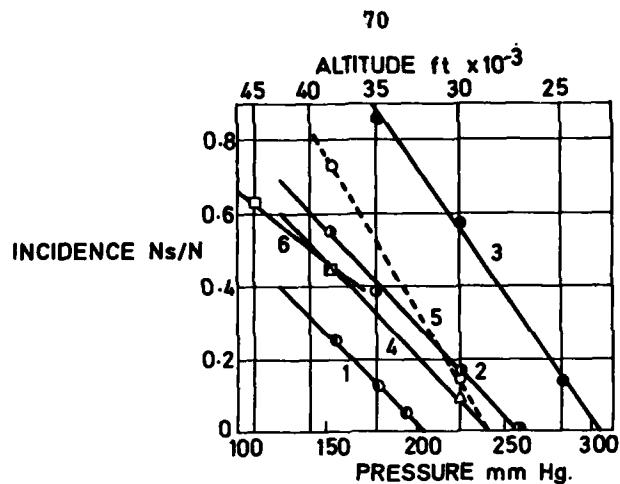
Fig. 5-1   Altitude/incidence relationship, as expressed by Nims (1951).

CRITICAL PRESSURE mm. MERCURY ABSOLUTE

CRITICAL DEPTH ft OF FRESH WATER

CRITICAL ALTITUDE ft

UPPER CURVE 1/κ = 5hrs
LOWER CURVE 1/κ = 1hr

ALTITUDE AND DEPTH
OF BODY SATURATION
BEFORE DECOMPRESSION

ABSOLUTE PRESSURES
CORRESPONDING TO UPPER
SCALE

mm. Hg.
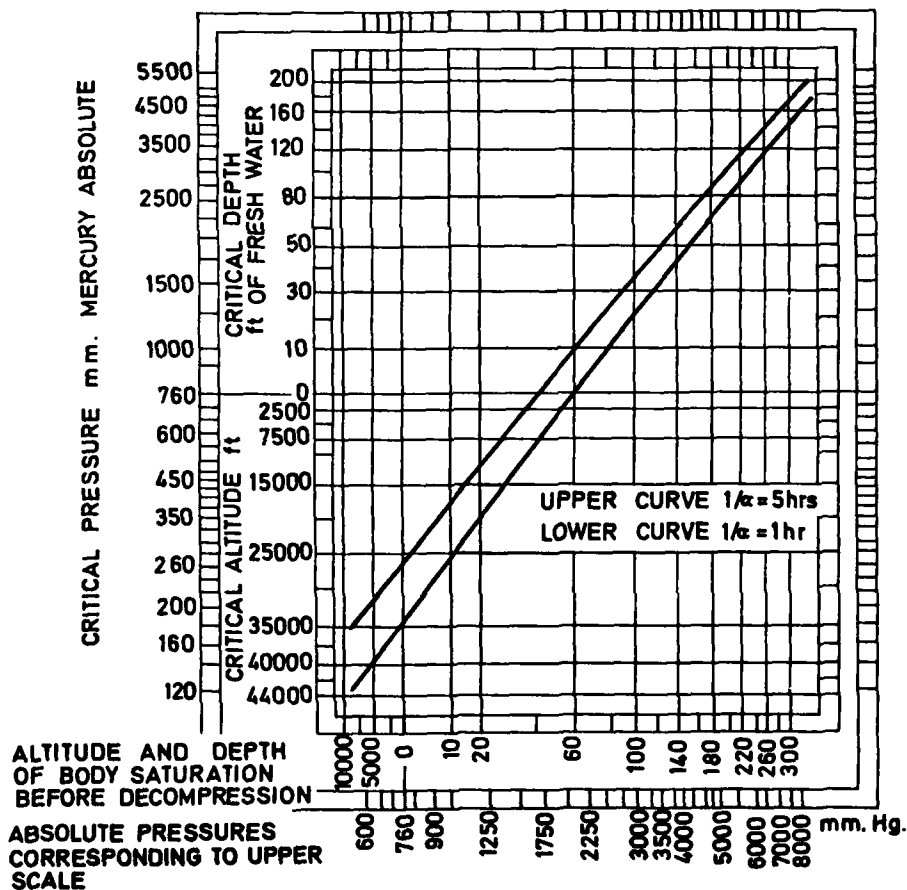
Fig. 5-2   Altitude/occurrence of symptoms, as expressed by
Bateman (1951).
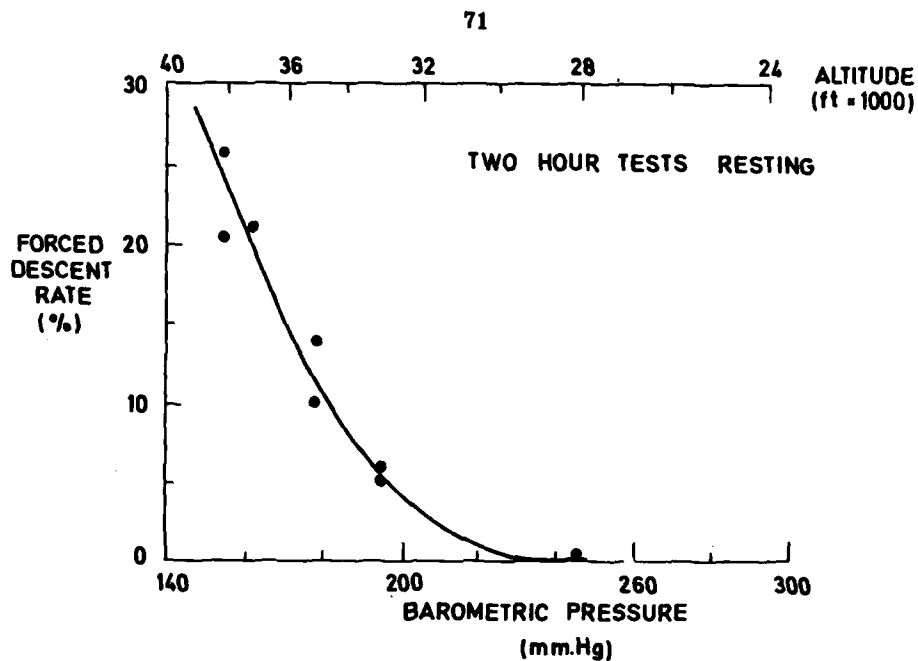
TWO HOUR TESTS RESTING

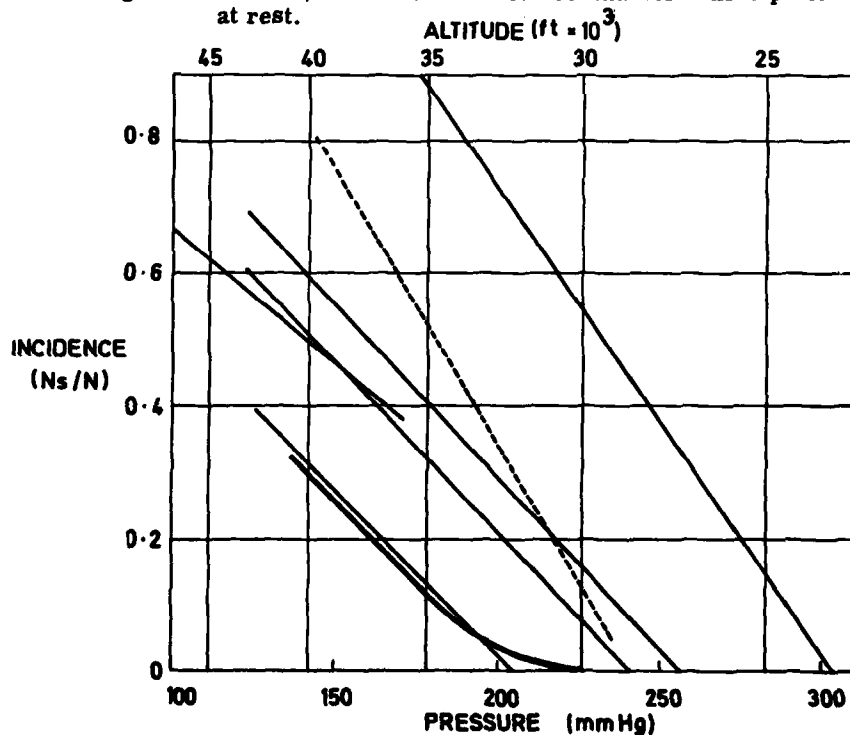Fig. 5-3 Altitude/incidence of forced descents for 2-hour periods, at rest.

Fig. 5-4 The derived curve of Figure 5-3 for 2-hour exposures at rest, superimposed as the heavier line upon the figure of Nims, Figure 5-1.

b)   a period of exposure of two hours.
c)   a regime of rest in the sitting position.
d)   forced descent as a measure of susceptibility.

Selected entirely on these criteria, the results of tests give Figures 5-3.
Examination of the co-ordinates of the experimental points reveals that they fall
very close to the plotted expression of the quadratic equation $y = 198.6 - 1.6799x + 0.00355x^2$.

The superimposition of the relevant lines from Nims' figure on Figures 5-3 yields
Figures 5-4.   It is apparent that the slopes are much the same for all but line five,
but that Nims' series, having included only one point illustrating an incidence of
less than 5%, has missed the inflexion of the curve at its lower end.   There can
be, as is shown later, no doubt of the genuineness of the incidence of over 1%
for forced descents following two hours exposure to 28,000 feet equivalent.

The Minimum Altitude

What altitude is the absolute minimum, below which cases cannot occur?
This is a very important question, particularly in the context of prolonged exposure
under conditions in which immediate descent is not possible, as for example,
in space flight.

Allan, in 1945, published a paper in which he expounded a quite revolutionary
view.   He encountered a young aviator who complained of pain in the left elbow
whilst flying at 12,000 feet.   On two subsequent flights he had pain at 10,000 feet.
In a decompression chamber the pain could be reproduced by ascent to 12,000-
15,000 feet.   He also studied a female decompression chamber attendant who
experienced pain and swelling of her foot at 18,000 feet.   Both cases were shown
to have underlying pathological changes.   The first had post-traumatic calcifica-
tion of soft tissues and the second aseptic necrosis of a tarsal bone.   Three other
individuals liable to experience pain in areas of adventitious calcification at
altitudes more conventionally regarded as hazardous were collected by Allan.
The first case has no parallel in the literature and must remain suspect.   There
is no evidence of an attempt to assess whether pain would occur at the same
altitude if the subject was unaware of the level attained.

Houston in 1947 reported on incidents arising during studies on acclimatisation and
noted five cases of pain in limbs at altitudes of 20,000 feet or below, including
one at 16,000 and another at 17,000 feet.   In these there may well be a very im-
portant source of difference from conventional cases.   His subjects were under-
taking serial ascents, for example forty-eight 'runs' in nineteen days.   If one
postulates bubbles persisting after descent one could perhaps envisage a bubble
expanding on ascent to an altitude at which it could not have arisen *de novo.*

The most striking and, it is contended, the most unequivocal case at low altitude
was seen by the writer in 1953 (Fryer, 1964).

Case 7

He was a pilot, aged 33, of portly build.   He had a long flying history, amounting
to some 4,800 hours. His health was good, although he had some years previously
been much troubled by osteomyelitis in the site of a fracture of his femur.   On
the day in question he took off at 08.30 in an unpressurised transport-type aircraft
modified for meteorological research work.   After about 2 hours' flight at a
maintained altitude of 18,500 feet he noticed blurring of his visual fields and
soon afterwards, an increasing sense of weakness.   He checked his oxygen supply

and found it to be fully serviceable. About one hour after the onset of visual dis-
turbance he noticed pain in both shoulders, quite severe in intensity. He later
developed tightness in the chest, worsening visual symptoms, severe headache and
after descent at the end of the nine-hour flight, he showed characteristic symptoms
and signs of post-decompression shock. There can be no doubt that this was a
genuine case of severe decompression sickness.

LeMessurier and Baxter (1964) have reported from Australia the results of
a survey of thirty-eight aircrew repeatedly exposed to altitudes of 20,000-24,000
feet. Nine gave histories of bends pain or other manifestations of decompression
sickness including visual disturbances, substernal pain and itching.

Damato, Kellett and Coburn (1965) have carried out prolonged experiments on
simulation of spacecraft atmospheric conditions. They report symptoms in eight
of seventy-three men exposed for long periods to pressures equivalent to 18,000
feet, six severe enough to warrant forced descents.

Finally, among cases referred to the writer following the reporting of symptoms
in flight, seven have had typical symptoms at cabin altitudes of 20,000 to 23,000
feet (three actually at 20,000 feet).

To summarise, there is considerable evidence of a threshold for decompression
sickness at 18,000 feet. Exceptional circumstances of repeated ascent would
perhaps explain the two cases occurring at 16,000-17,000 feet (Houston, 1947).
The isolated case of Allan at 10,000-12,000 feet remains unique and may perhaps
be regarded as being spurious association between altitude and pain at the site of
gross pathological tissue change.

It is of considerable interest that the pressure at 18,000 feet is 379 mmHg, almost
precisely $\frac{1}{2}$ atmosphere. This threshold corresponds remarkably with that
first postulated by Haldane in 1907 in his report to the Lords Commissioners
of the Admiralty on deep diving, namely that ascent was safe only to a limit of a
pressure ratio 2 : 1.

Base Altitude Before Ascent

When reference is made to altitude in the aviation context, it is always based upon
standard conventional pressure tables. What if the altitude from which ascent
is initiated is not that of conventional sea level or 760 mmHg? Clearly, whether
one considers absolute or relative pressure change as relevant to the occurrence
of symptoms, base altitude may be of considerable importance.

Even at a fixed point on the earth's surface barometric pressure varies continuously
as masses of air of varying temperature and therefore varying density move both
horizontally and vertically. Conventionally such changes of pressure are mea-
sured in millibars (1013.2 mb = 760 mmHg). With changing meteorological
conditions local atmospheric pressure commonly fluctuates over a range of some
30 mb, equivalent to a fluctuation of some 700 ft about sea level. Do local changes
of this sort influence susceptibility?

In an attempt to answer this question, records have been examined for one R.A.F.
decompression chamber at which some 2,000 man runs were executed in a period of
902 working days. From the meteorological station sited on the airfield barometric
pressure observations for 0900 and 1400 hours GMT were obtained. These
times correspond withe customary hours for the initiation of decompression tests.
The number of half-days on which given barometric pressure readings were
recorded was calculated; the results are shown in Table 5-1.

Table 5-1. Symptom-producing tests related to local barometric conditions.

Barometric Pressure Range (millibars)	Number of half-days	Half-days on which symptoms occurred	
below 999	322	16	
1000 - 1004	173	5	
1005 - 1009	261	6	
1010 - 1014	312	12	
1015 - 1019	292	11	
1020 - 1024	261	15	
1025 or over	183	4	
Total	1,804		

Table 5-2. Time of forced descents, (data of Motley, Chinn and Odell, 1945).

Time period	Number forced to descend	% of total
0-10 min.	17	2.3
11-20 "	72	9.6
21-30 "	125	16.7
31-40 "	136	18.1
41-50 "	192	25.6
51-60 "	208	27.7
	750	100.0

Against each pressure-range is also shown the number of the relevant half days on which one or more cases of decompression sickness were recorded.

Statistical evaluation of Table 5-1 shows no significant relationship between the prevailing ambient pressure and the proportion of half-days yielding cases.

Although a relationship between the occurrence of cases and abrupt changes in local barometric pressure would seem inherently improbable, the data for the same R.A.F. station were examined in this respect.

The twice-daily readings were plotted on a chart and three states were defined; they were conditions of rise or fall of pressure by 20mb or more over seven day periods and steady or near-steady conditions. Runs in which cases occurred were then analysed accordingly and no perceptible trend towards occurrence in either of the unstable pressure conditions could be detected.

Much greater differences in initial pressure may result from the elevation of the sites from which ascent is made. Fraser (1943) is cited by Bateman (1951) as having demonstrated a lower incidence of symptoms among personnel living at Regina and Edmonton in Canada, 1,900 and 2,200 feet above sea level respectively.
Cheetham (1947) reported on the use of a decompression chamber in Lyttleton, Transvaal, 4,700 feet above sea level. Only twenty-eight officers were tested, but there were eighty-three man-runs of three hours at 37,000 feet, a severe stress. Only sixteen runs resulted in symptoms and less than 4% of runs resulted in symptoms severe enough to warrant rejection. This rate is extremely low compared with any other data for this altitude and duration of exposure.

Fraser is cited as having artificially induced resistance by keeping subjects at a simulated 7,500 feet for ten to thirty-three hours before ascent to 35,000 feet. Marbarger et al (1957) similarly protected subjects by allowing them to remain at a pressure equivalent to 12,000 feet for only four hours before ascent. Protection of this sort is far from complete. The writer has carried out tests on ten aircrew, subjecting them to three hours air-breathing at 8,000 feet before ascent to 40,000 feet. Six of the ten were incapacitated within one and three-quarter hours and the run was discontinued. Clearly three hours exposure to 8,000 feet offers little or no protection.

Rate of Ascent

Since the earliest years of this century it has been recognised, in compressed air work and in diving, that decompression sickness may be prevented by adoption of a slow ascent to a pressure equivalent to half absolute working pressure (or a little above) and then decompression at a rate of several minutes per pound per square inch pressure. The assumption is that, if the ascent rate is slow enough, blood and tissues desaturate with regard to inert gas sufficiently to preclude the development of a degree of supersaturation likely to cause bubble formation on a scale associated with symptoms.

Armstrong, in 1939, extrapolated from the work of Haldane on diving tables and calculated that ascent at a rate not exceeding 78 feet per minute would be unassociated with bubble formation. No experimental test of this supposition has been reported, but in the files of the Institute of Aviation Medicine is to be found an account of a decompression apparently designed to investigate this very point. Brief mention of the result was made in an anonymous report to the Flying Personnel Research Committee in 1941.

On 8th February, 1941, a subject, R.W., was decompressed at a rate of 50 feet per minute; he was oxygen-breathing from ground level. At 18,650 feet skin itching was noticed, at 25,800 a slight limb pain was noticed, at 27,500 feet the discomfort became quite definite, in the region of the left knee and at 34,000 feet moderate pain was present in the knee and ankle. By the time that 37,000 feet was reached severe pain in both knees was barely tolerable. At 38,000 feet the pain waxed and waned, but one hour after the maximum height of 38,000 feet had been reached, the pain suddenly became so serious that descent was imperative. The theory of Armstrong was clearly not tenable.

Long and exhaustive series of experiments on groups of men would be required to investigate fully the effects of varying rates of ascent within the practical aviation range, say 500 ft/min. to very rapid ascents taking a matter of seconds only. Nims (1951) looked at available data and found it insufficient to base judgment on, although the data of Griffin et al (1943) suggest strongly that the rate of affection of subjects is higher after an ascent at 5,000 ft/min. than after ascent at one fifth of that rate. The whole question of attempting to estimate the rate of denitrogenation during ascent is grossly complicated by the effects of such variables as the time/concentration relationships of oxygen inhalation and the possibility of the occurrence of 'seedling' silent bubbles, etc. In practice, it is generally recognised that wide variations in ascent rates are without great effect on outcome. For example, Fraser in 1942 could detect no difference between ascents to 35,000 feet taking fifteen minutes or sixty minutes, followed by two hours sojourn at the full height. The ineffectiveness of adoption of a rate of under 50 ft/min. is a clear indication of the non-validity of theoretical reasoning based simply on Haldane-type calculations.

Period of Exposure

For many reasons it is important that the time-course of decompression sickness should be understood. From the point of view of theory-construction concerning bubble formation, it is of great interest to know the rate of occurrence of new cases with the passage of time. In terms of practical aviation and space medicine it is most important to know whether there is a maximum period beyond which new cases will never arise.

Not surprisingly the time of onset has been calculated for a number of decompression tests. The largest series was that of Motley, Chinn and Odell (1945) who could extract from their data the time of forced descent but not the actual time of onset. They calculated the proportion of total descents in each ten minute period of the one hour test at 30,000 feet. These data appear to be derived from a test which was not as straightforward as one might hope, since some subjects were exposed to 18,000 feet, air-breathing, for a period to demonstrate the effects of hypoxia before ascent was resumed to the higher altitude.

In their original form, Motley and Chinn's figures are given in Table 5-2.

Cumulative plots of incidence have been published in many papers, for example Figure 5-5 from Fulton (1951) and Figures 5-6 and 5-7 from Fryer (1965B) and complex mathematical indices have been calculated (Ryder et al, 1945). It is not easy however to understand the real implications of the available data. Nims (1951) produced lengthy formulae in which, by adjustment of three constants, a curve could be described which would approximate to observed incidence data (Fig. 5-8). This form of expression, however, indicated a decrease of incidence to almost zero after some two hours, a figure not compatible with Figure 5-6.

% INCIDENCE

○ TOTAL BENDS
● FORCED DESCENT

100 ⊢

EXERCISE (158 SUBJECTS)

80 ⊢

60 ⊢

REST (90 SUBJECTS)

40 ⊢

20 ⊢

0   40   80   120   160

TIME (min)
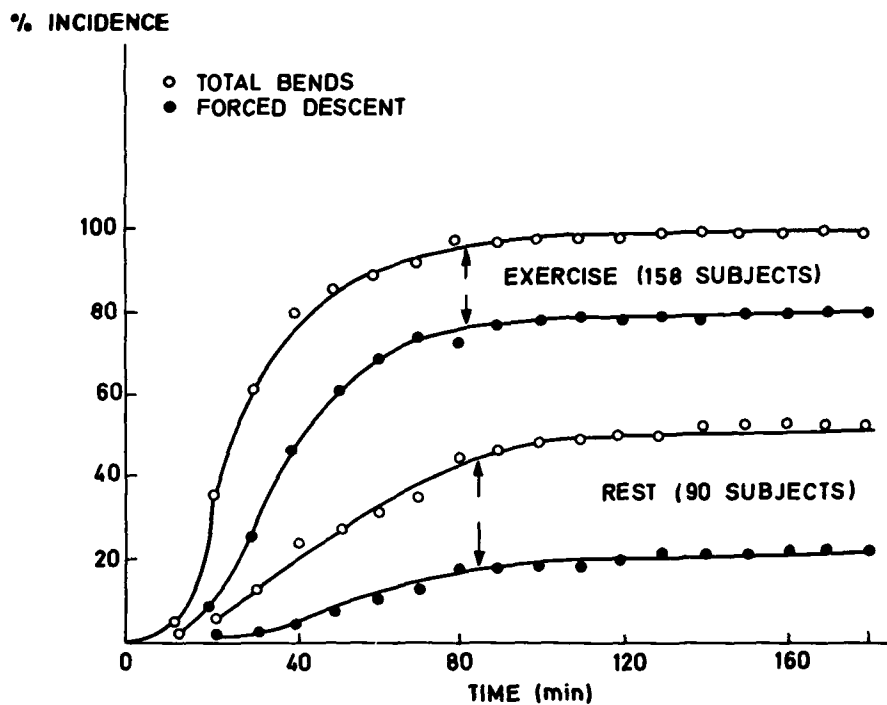
Fig. 5-5   Time/incidence data, from Ferris and Engel (1951).   Cumulative incidence of bends and forced descent from bends during exercise and rest in 3-hour, 35,000-foot flights.
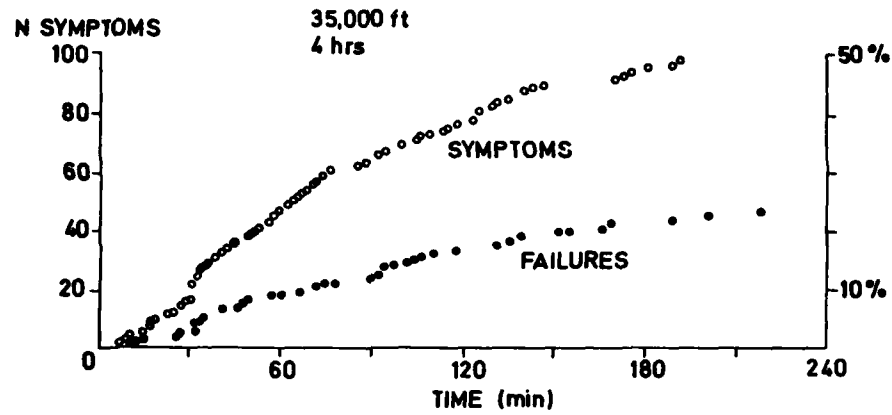
Fig. 5-6   Time of development of symptoms;   original data.
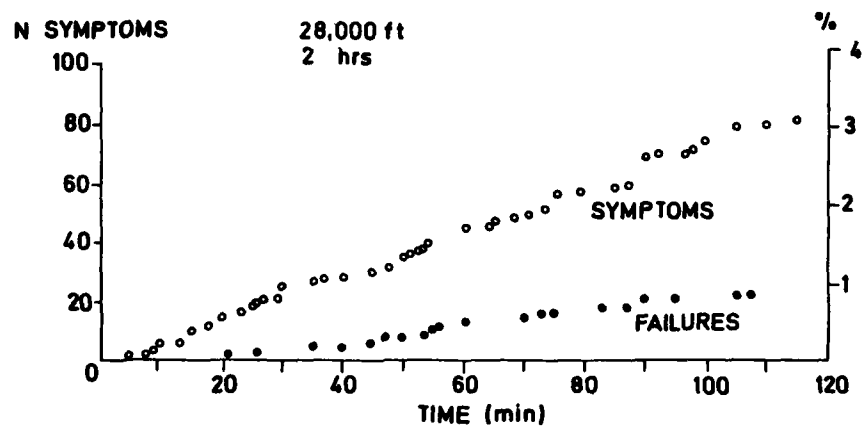

Fig. 5-7   Time of development of symptoms;   data derived from
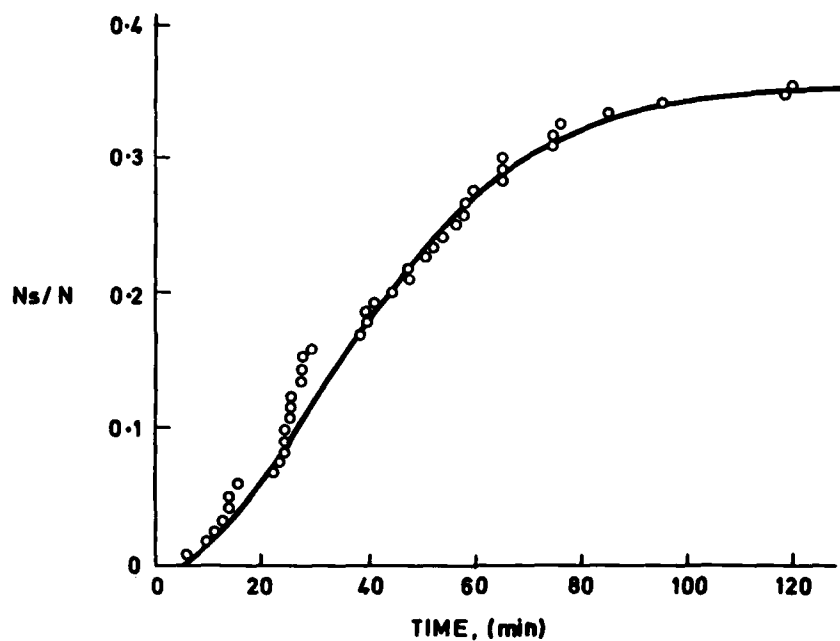Russell (1943).

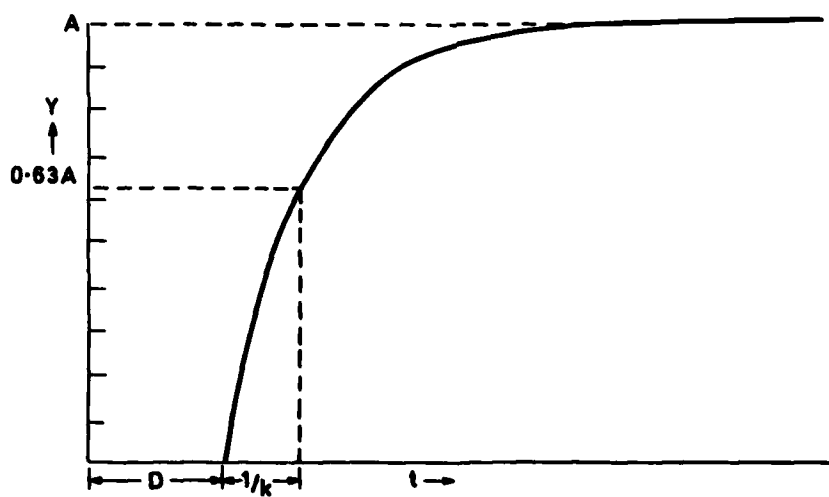Fig. 5-8   Time/incidence data;   from Nims (1951).

Fig. 5-9   Graphical expression of the exponential function,
$y = A (1 - e^{-kt})$.

All curves of incidence versus time appear to be sigmoid. If one ignores the foot of the curve and takes a point corresponding to about 20% of the eventual total of sufferers, the remaining points give the impression that they might lie on an exponential curve, a common form of relationship in biological data. Now, an exponential curve as shown in Figure 5-9 has the following characteristics:

(a) the relationship between t and Y is such that $Y = A(1 - e^{-kt})$

(b) A represents the maximum attained value of Y, when t = infinity

(c) k is such that at time $1/k$, $Y = 0.63A$

Suppose that the relationship between incidence Y and time t is exponential, it becomes apparent that A represents the ultimate proportion of susceptibles and k the time constant of a particular exposure. There is also a factor D which indicates the delay between attainment of altitude and the intercept on the t axis.

With the aid of an electronic analogue computer and a display oscilloscope it is possible to set up visual representations of exponential functions. The characteristics of these may be adjusted by varying the values of A and K until one obtains a best-fit to data plotted on an overlying sheet of transparent paper. Having thus chosen values for k, A and D it is possible to fashion a permanent resultant curve speedily with an electro-mechanical X-Y plotter. Using these techniques with the help of the Instrumentation and Electronics Section of the Institute of Aviation Medicine it has been possible to examine twelve sample sets of data. The results are shown in Figures 5-10 to 5-17 and in Table 5-3.

From examination of these it should be possible to answer several quite fundamental and vital questions.

For example:

(a) Do the data match exponential curves?

Apart from the foot portion of the curve, they all seem so to do.

(b) Is the ultimate incidence in any run likely to be 100% ?

If so, A would always be 100. A curve in which A > 100 would make nonsense of such a proposition. In fact, no value of A greater than 100 is found in the twelve examples. However, only those curves in Figures 5-10, 5-11 and 5-12 have A values of the order of 100. Those in Figures 5-13 to 5-16 range from 24 to 74 and those in 5-17 are 7 and 3 (see Table 5-3).

This result implies that for certain conditions some persons in a group will never develop symptoms, regardless of the duration of the exposure. The validity of this proposition is indicated by the mis-fit of curves deliberately calculated on the premise that A = 100 (the dotted curves), in Figures 5-13 to 5-16.

(c) Is the rate of occurrence of symptoms similar in different exposures?

If so, k would be consistently similar. Examination of Table 5-3 shows this not to be so.
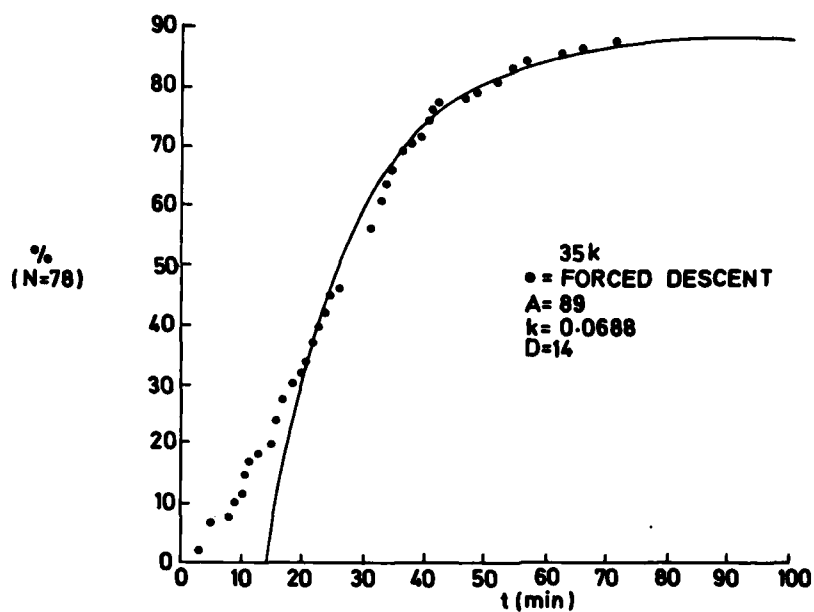
Fig. 5-10 Cumulative incidence of forced descents; data from
Ryder et al (1945).
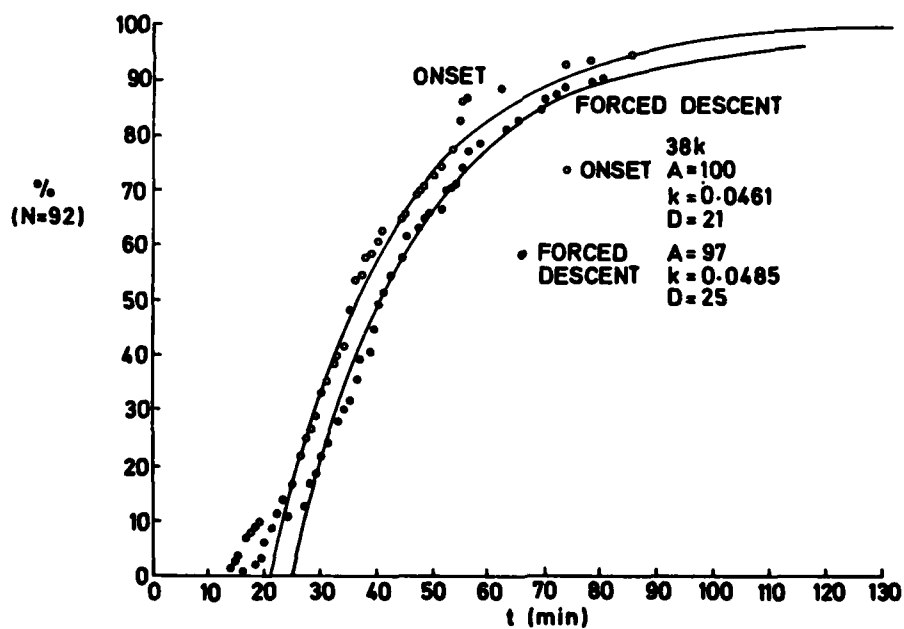
Fig. 5-11 Cumulative incidence of symptoms and forced descents;
data from Grenell et al (1944).
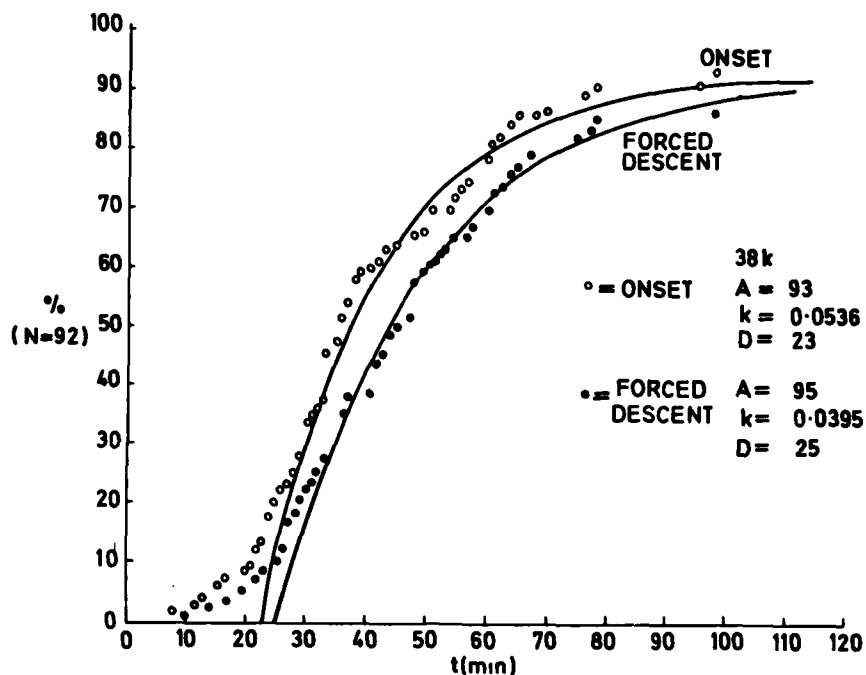
Fig. 5-12 Cumulative incidence of symptoms and forced descents; data from Grenell et al (1944).
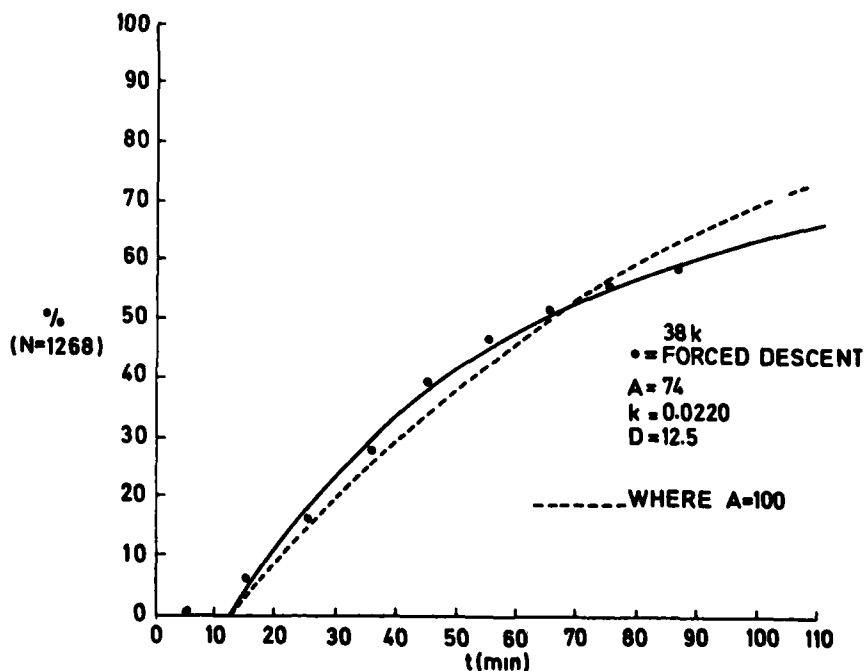
Fig. 5-13 Cumulative incidence of forced descents; data from Stewart et al (1943).
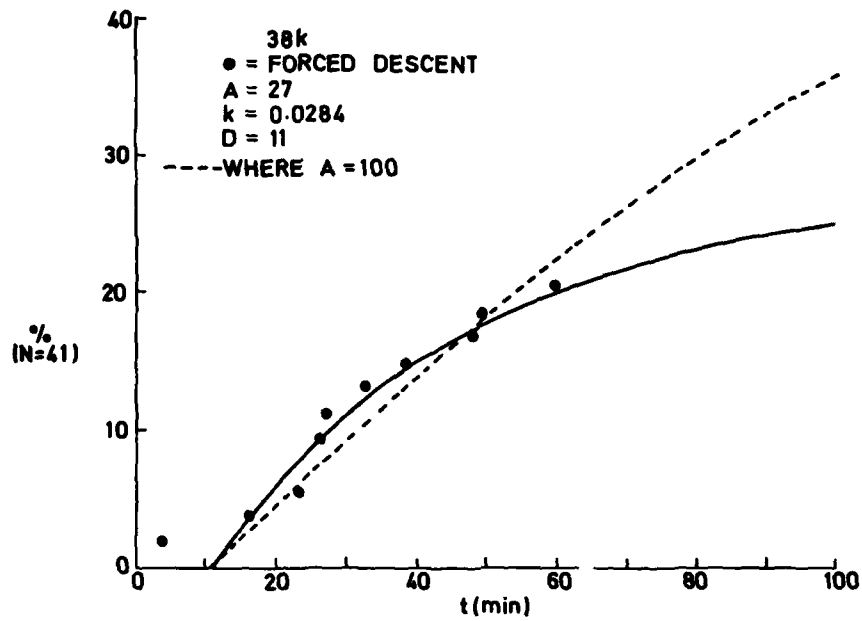
Fig. 5-14   Cumulative incidence of forced descents;   data from
Robinson (1944).
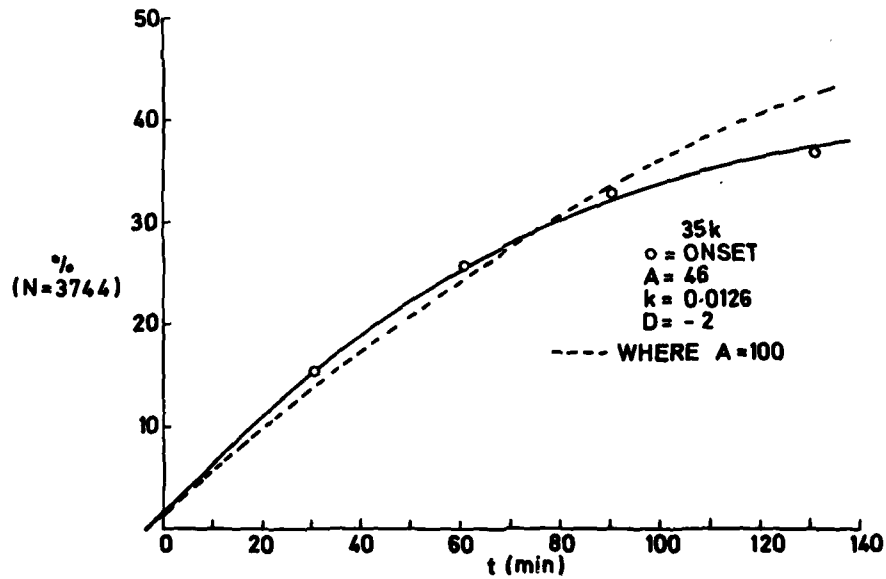
Fig. 5-15   Cumulative incidence of symptoms;   data from
Stewart et al (1943).
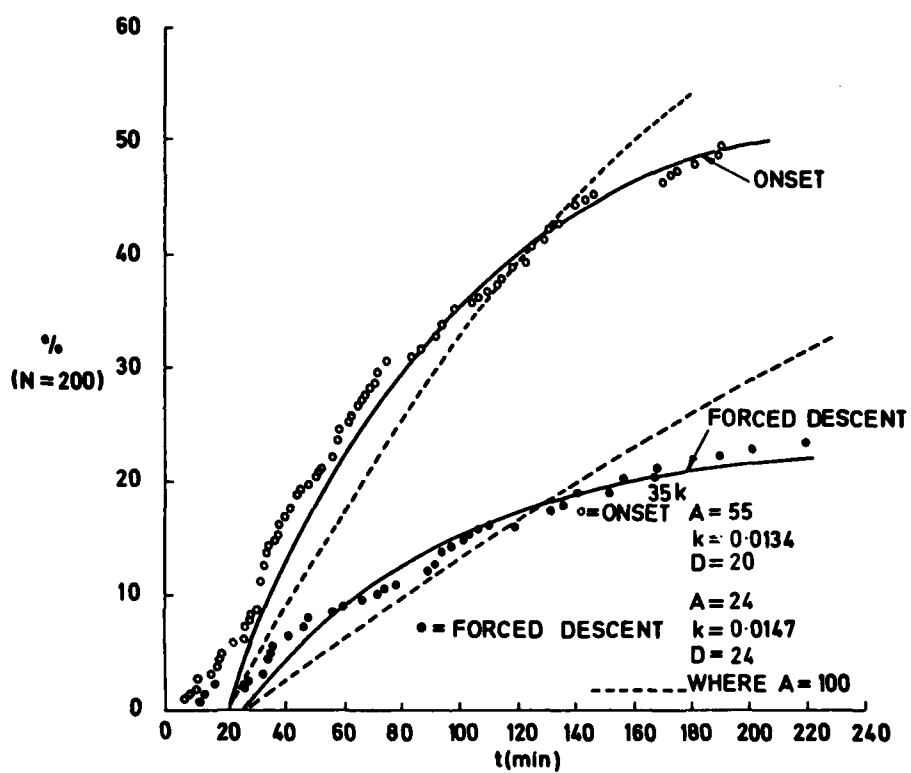
Fig. 5-16   Cumulative incidence of symptoms and forced descents;
data derived from Russell (1943).
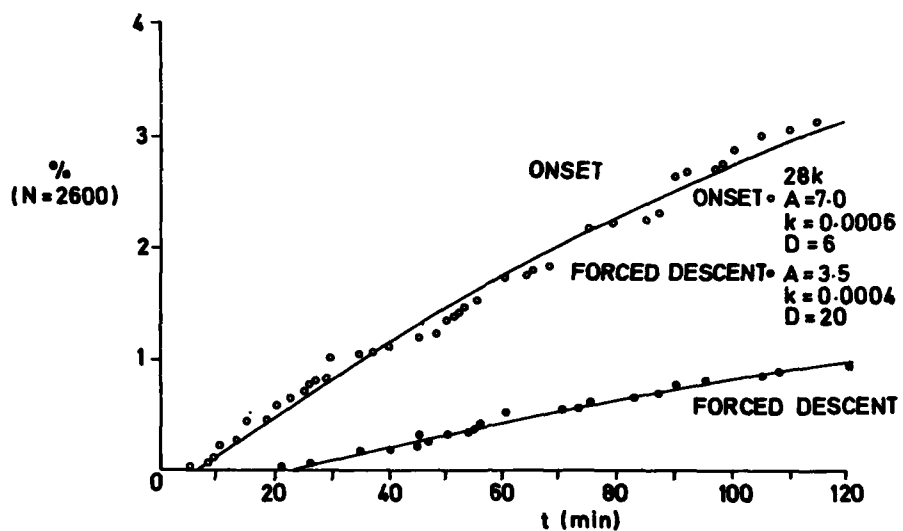
Fig. 5-17   Cumulative incidence of symptoms and forced descents,
original data.
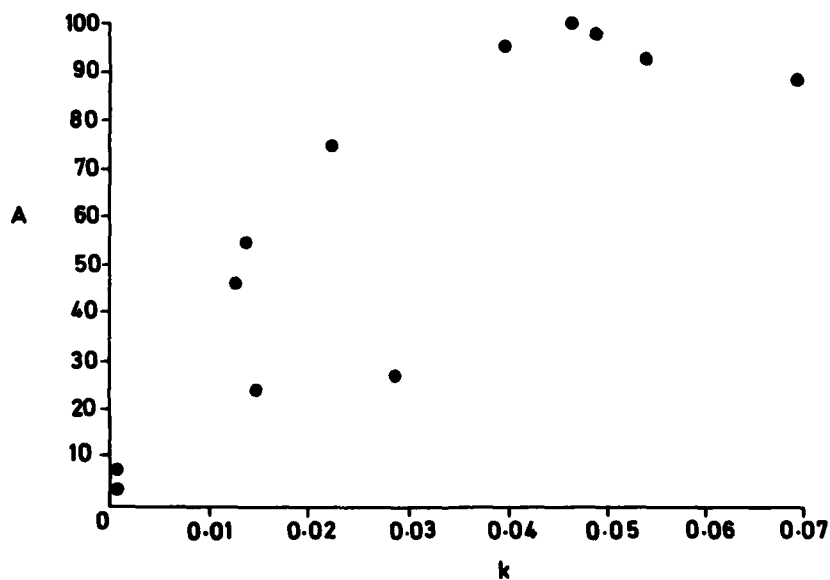
Fig. 5-18   The relationship between the values of k and A from
Figures 5-10 to 5-17 inclusive.

Table 5-3   Time of descent analysis.
Data relevant to curves in Figures 5-10 to 5-17.

Figure Reference	A (%)	k	$1/k$ (min.)	D (min.)
5-10	89	0.0688	14.5	14
5-11	(100	0.0461	21.6	21
	(97	0.0485	20.6	25
5-12	(93	0.0536	18.7	23
	(95	0.0395	25.3	25
5-13	74	0.0220	45.5	12.5
5-14	27	0.0284	35.2	11
5-15	46	0.0126	79.4	-2
5-16	(55	0.0134	74.6	20
	(24	0.0147	68.0	2/
5-17	(7	0.0006	1667	6
	(3.5	0.0004	2500	20

Figure Reference	$1/k + D$ (min.)	Altitude (ft x 1000)	Criterion (Onset or Forced Descent)
5-10	28.5	35*	F.D
5-11	42.6	38*	O.
	45.6	38*	F.D.
5-12	41.7	38*	O.
	50.3	38*	F.D.
5-13	58.0	38*	F.D.
5-14	46.2	38	F.D.
5-15	77.4	35	O.
5-16	94.6	35	O.
	92.0	35	F.D.
5-17	1673	28	O.
	2520	28	F.D.

* = exercising

If $1/k$ is calculated for each case and the delay D is added, the time at which 63% of the ultimate total of cases will have occurred can be calculated. It is clear that this is not consistent.

(d) Is there a constant delay in the onset of first symptoms?

From all examined series it would seem that the first case rarely occurs before some five minutes have passed at altitude. The value of D in the series analysed here is fairly narrow in range, from six to twenty-five with a mean value of 17.75 min.

(e) Are the rate of accumulation of cases and the ultimate total associated?

If so, A and k should be directly related. Figure 5-18 shows that this is so, although there is considerable scatter.

(f) Are the rate of accumulation of cases and the altitude of exposure related?

Here, examination of Table 5-3 shows that this inherently probable relationship is not proven.

(g) What, if any, is the time after which no further case is likely to appear?

Here the analysis cannot help us. Reference to the literature, however, gives one astounding observation; Morgan et al (1963) had a case of apparent chokes on the ninth day of a prolonged space-flight simulation.

To summarise, the occurrence of cases with time generally conforms to a sigmoid distribution, the convex portion of which is exponential. The ultimate total of cases in some tests is 100% of those exposed, in others less.

The rate at which cases accumulate seems independent of any factors examined and the time course of the morbidity rate would seem a characteristic of every set of experimental conditions.

Temperature

The literature on the effect of external temperature on the incidence has been reviewed by Nims (1951) and by Cook (1951). To summarise the main observations, Fraser and Rose (1942) showed a definitely increased susceptibility to decompression sickness at -10°F compared with +70°F. Anthony et al (1943) showed a similar effect comparing +55°F with +100°F. Some rather contradictory evidence was adduced by other workers who confused the experimental design by using heated clothing in cold environments. Griffin et al (1943) showed however, that the incidence in three conditions they studied increased in the sequence warm (+80°F) < cold (+32°F to -5°F) but wearing heated clothing < cold (+32°F to -5°F) inadequately clothed.

In practice it has often been the writer's opinion that local cold had increased the susceptibility to bends. Several navigators in Canberra aircraft have related their bends pain to the fact that their crew station is, in that type, particularly cold. It is not uncommon to observe frost on exposed metal even in relatively short flights. The pilot's position, on the other hand, is generally warm and often excessively hot owing to the solar radiation load through the extensive cockpit transparency. It is of considerable interest that the incidence of bends in Canberra pilots is very much lower than that in navigators.

Summary

The incidence of decompression sickness, being related to a pressure reduction is therefore affected by base altitude, rate of ascent and final altitude. The most important in practice is the latter and expressions are derived for the results of standardised exposures of comparable groups to various heights.

The period of exposure is also of great significance and the possibility of deriving mathematical expressions of the relationship between incidence and time has been examined, with disappointing results.

Finally, evidence has been found that cold may be responsible for an increase in susceptibility.

6

Individual Factors Affecting Susceptibility

Introduction

It will be recalled that in the preceding chapter, factors which affect symptom occurrence were divided into two broad but not totally distinct groups; environmental and individual. It is within the latter that perhaps some of the strangest enigmas of the subject lie.

We have seen that an exposure of a group of subjects to altitude may lead to the development of symptoms in a proportion of that group, and that the degree of the susceptibility is related to such factors as exposure time, altitude and initial (base) altitude. What we need to know when examining an operational situation is the magnitude of the risk of the occurrence of symptoms. But what does a decompression sickness incidence of x percent mean in terms of personal reaction? What the physiologist and physician should be concerned with in this respect is once more a matter of accurate characterisation. Put in its simplest terms, the question which must underly all investigations is what is meant and implied by 'susceptibility'?

For example, suppose a set of conditions, carefully controlled, yields symptoms of decompression sickness in ten of a group of one hundred men. Firstly, if the test were to be repeated, we have already seen that a very similar attack rate would be expected, but are there minor fluctuations attributable to any identifiable agencies acting on the group? Secondly, if the same test were to be repeated ten times, on each occasion yielding the same 10% morbidity, would the same ten men be affected each time (true individual susceptibility), would each man be affected once (a random process) or would there be an intermediate result, say 1 case affected 10 times, 2 nine times, 2 eight times, 2 seven times, 2 six times, 2 five times, 2 four times, 2 thrice, 2 twice and 2 once? Thirdly, is there any determinable characteristic of an individual which would enable one to forecast susceptibility?

The Method of Investigation

The only means whereby these three questions may be investigated are painstaking observation and analysis of controlled exposures of men in large numbers. The literature abounds with collections of rather indifferently administered tests, carried out under the difficult circumstances of war and also there are large numbers of descriptions of deliberate tests involving repeated exposures of small groups of research workers or students. In the former case records are often incomplete, procedures in different centres are not strictly comparable, tests are of very complex character (for example Motley, Chinn and Odell's series (1945) included simple ascents, two stage tests, hypoxia experience and varying degrees of denitrogenation during ascent) and incentives to complete the test may be highly variable. In the second experimental group, cumulative effects may cloud the

issue, a small sample may give results very misleading in comparison with a large population and unconscious bias is very likely when the investigator is either the subject or is in direct control.

In studying this aspect of the subject the writer has not merely drawn upon the literature and the large experience of cases referred for opinion. The major part of the survey has been conducted on the records of a decompression test applied to R.A.F. personnel during the period 1957-1961. This test was designed with great care to ensure the maximum consistency in clinical appraisal, application of the test and documentation. The resulting records were analysed (Fryer, 1965B) and proved almost ideal for that purpose with the exception of one aspect only, that of measurement of stature. The possibility of poor standardisation during the shake down period of application of such a procedure having an adverse effect on the overall analysis, was avoided by restricting the block of data analysed to a period commencing some three years after the initial instruction was issued.

The High Altitude Selection Test

The aim of the test was the detection of susceptibility under conditions likely to be encountered in flight. For this purpose the profile selected was ascent at 5,000 feet per minute (later slightly but apparently insignificantly altered to 4,000 ft/min. to 20,000 feet, 3,000 ft/min. above that level), to 28,000 feet followed by two hours sojourn at that level. The test was to be repeated with a minimum of forty-eight hours and a maximum of thirty days unless particularly severe symptoms were encountered. Symptoms were graded as mild, moderate or severe according to carefully defined criteria and the result in terms of pass or fail was determined on the following basis:

Mild + Mild			Moderate + Mild		
Mild + Nil		pass	Moderate + Moderate		fail
Moderate + Nil			Severe		
Nil + Nil					

Details of the sample are given in the Appendix. Briefly, almost 5,000 exposures of 2,606 men were analysed. Unless otherwise stated below, the data in the remainder of this chapter are derived from this analysis.

Sub-Group Factors

There could conceivably be factors which would affect a group, as typified by those men reporting for test at a particular place, on a particular day, at a particular hour. Some possible factors have been examined. Elsewhere we have reported on the negative findings in connection with the prevailing barometric conditions.

Place

It was not possible to compare stations with any confidence, since the characteristics of the personnel varied so markedly; for example young, fit, flight cadets at one station, senior aircrew converting to advanced aircraft types at another and senior officers attending refresher courses at a third.

Day

Quite conceivably the day of the week could affect the outcome of a test should there be a relationship between prior activity and susceptibility. Examples might

Table 6-1   Symptom distribution by day of week

Day	Number of cases	Proportion of total
Monday	47	28.5%
Tuesday	25	15.2%
Wednesday	45	27.3%
Thursday	30	18.2%
Friday	17	10.3%
Saturday and Sunday	1	0.6%

Table 6-2   Relationship between tests and symptoms, by day of week

Day	Proportion of total cases	Proportion of tests
Monday	28.5%	25.1%
Tuesday	15.2%	21.9%
Wednesday	27.3%	23.2%
Thursday	18.2%	16.2%
Friday	10.3%	11.4%
Saturday and Sunday	0.6%	2.5%

be week-end sport, travelling, gardening or party-going affecting Monday results and the traditional Wednesday sports afternoon influencing Thursday tests.

The analysis of symptom occurrence day-by-day is given in Table 6-1.

This skew distribution must be compared with that of actual tests carried out, shown in Table 6-2.

It can be seen that there is no obvious enhanced susceptibility on any particular day. This is in agreement with the finding of Motley et al (1945) whose group, although much larger, was much less uniformly tested.

Hour of Day

Motley et al (1945) noted in their analysis that the incidence of symptoms was highest in the morning and lowest in the late evening. Their data are given in Table 6-3.

Table 6-3   Incidence related to time of day, (after Motley, Chinn and Odell, 1945)

Time	0600-1000	0900-1300	1300-1700	1600-2400	1930-2230
Total bends incidence	17.9%	16.6%	15.5%	15.5%	11.6%

It will be noted that their selection of periods follows a bizarre pattern with over-lap of all groups with one or both adjacent groups. Swann and Rosenthal in 1944 found a similar distribution in a small series (Table 6-4).

Table 6-4   Incidence related to time of day, (after Swan and Rosenthal, 1944)

	Morning	Afternoon
Bearable bends	13.4%	9.7%
Unbearable bends	4.9%	3.9%

Their figures were statistically proven to be significant. Guest (1944) reported the same trend in over 5,000 cases, with a very low incidence in a small group tested during night-time.

In our own experience a similar relationship has been demonstrated.

Table 6-5   Incidence related to time of day, own data

	Morning	Afternoon	Not known
Total distribution of tests	69.8%	26.1%	4.0%
Proportion of total cases	76.4%	17.6%	6.0%

To what may we attribute this difference? Activity during the day may lead to a constitutional change which is reflected in lowered liability to experience symptoms of decompression sickness; no evidence is available on which to assess this possibility. Swann and Rosenthal (1944) ingeniously suggested that diurnal variation in body temperature may be responsible for this effect of time of day. Unfortunately their data for bearable bends versus oral temperature show no correlation and, although they claimed a reduced incidence of intolerable bends in a group with a temperature of over 98.6°F when compared with another group of temperature less than 98.0°F, examination of their raw data would suggest that this relationship was purely due to chance, the figures for each 0.1°F group being apparently randomly distributed about the mean (Fig. 6-1).

No really satisfactory explanation had been proposed for the diurnal fluctuation in susceptibility.

Susceptibility of the Individual

Although all workers in the field of decompression sickness can cite examples of known susceptibles they equally well are aware of surprise cases, occurrence of symptoms in those generally quite untroubled under identical conditions of exposure It is necessary to investigate thoroughly the second question posed at the beginning of this chapter; does the condition affect a random sample of identical size in a given population or are there truly highly susceptible individuals?

The literature on altitude tests contains several small scale investigations of this question, from six exposures of seven men to two ascents by groups of over one hundred. The results have been reviewed by Henry and Ivy (1951) and were thought by them to indicate the existence of true susceptibility but the figures were far from ideal for the purpose of the analysis of this particular aspect.

In the case of the 2:,000 foot test we are able to conduct an analysis of figures which are much more suitable for the investigation of this vital problem. The men were subjected to a relatively mild procedure with a remote chance of seeing or experiencing very severe reactions. They were assured of an interval between tests which is known to preclude temporary enhancement following experience of symptoms. They were maintained at rest, thus eliminating the chance of inequality of level of exertion between runs or between individuals. They were adequately briefed and had no need to fear reporting symptoms since mild manifestations on both runs were consistent with a pass result.

In analysing these figures it is felt that the most useful approach is to assume that before a test individuals are of unknown potential and that they can be revealed as being of one of three categories: unaffected, mildly affected and seriously affected. For convenience these categories are represented by shading in Figure 6-2.

It can be seen from Figure 6-2 that, of the total, 3.2% declared symptoms and that of these 16% were of such a nature or severity as to make further exposure undesirable (an assumption at this stage based more on intuition than on scientific knowledge).

For the second test, illustrated diagrammatically in Figure 6-3, the identity of those exposed has been concealed by indicating the group presenting as being of uniform composition. The overall result is a symptom rate of 2.7%, slightly lower than that of the first test. The proportion of severe reactions is similar to that of the first test, 18.6%.

If one enquires further about the composition of the second test group, the implications of the occurrence of symptoms on the first run are immediately apparent.
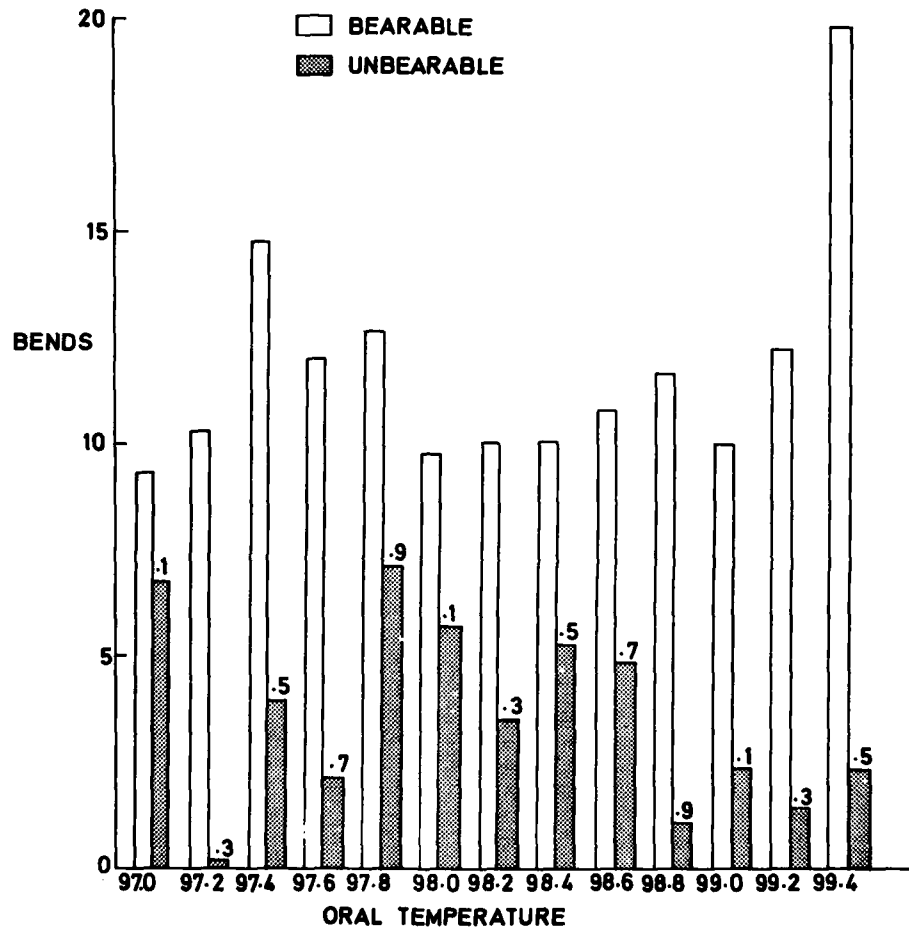
Fig. 6-1   The incidence of bends related to oral temperature.
Reproduced from Swann and Rosenthal, (1944).
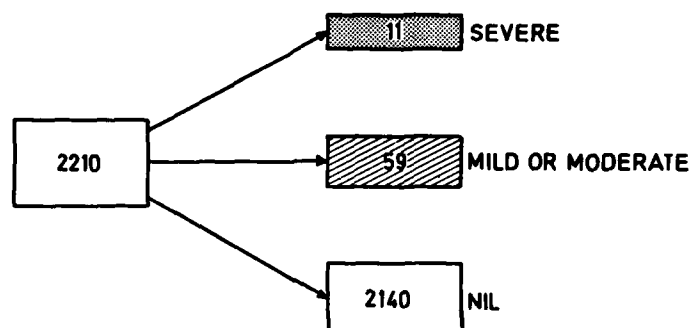
FIRST TEST-3·2 % SYMPTOMS

Fig. 6-2   Repeatability data from duplicated 28,000 foot test.
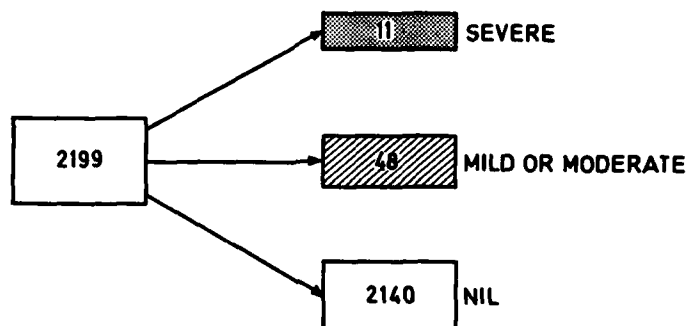
SECOND TEST-2·7 % SYMPTOMS

Fig. 6-3   Repeatability data from duplicated 28,000 foot test.
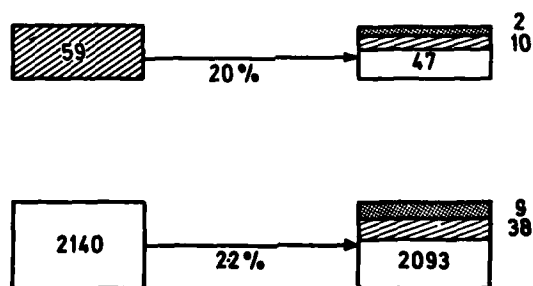
SECOND TEST - RELATED   TO   FIRST

Fig. 6-4   Repeatability data from duplicated 28,000 foot test.
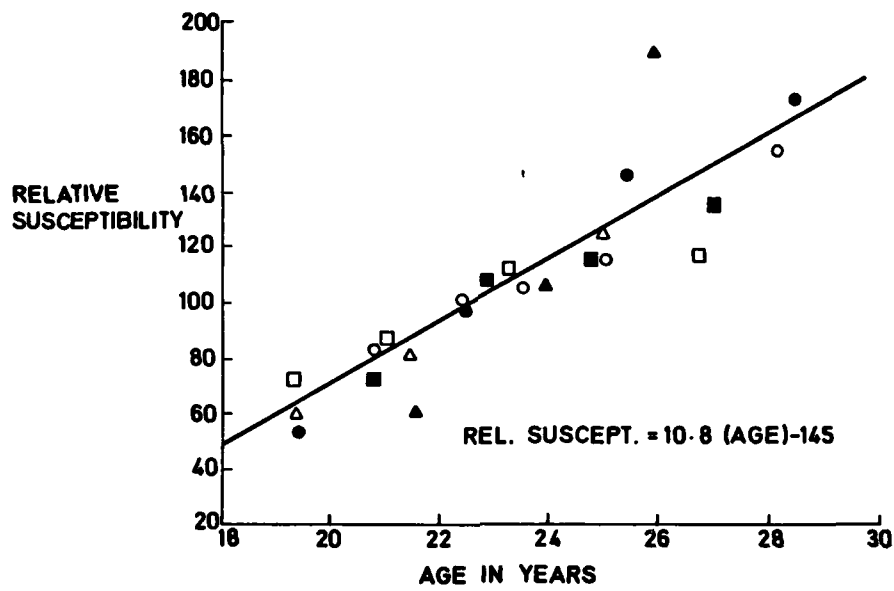
Fig. 6-5 Susceptibility to decompression sickness related to age
(Gray, 1951).

Figure 6-4 shows that those of the mildly affected category from test 1 have a symptom rate of 20% on the second exposure, whereas their colleagues have a rate of 2.2% only. The difference is highly significant.

These results it is believed are the clearest indication of a true factor of individual susceptibility in a large and unselected group, not subjected to very severe conditions and, it is believed, not in any way temporarily rendered non-uniform by re-testing within too short an interval.

Age

In the period of over 100 years since the first recognition of decompression sickness, workers in this field have asserted that age has an adverse effect on tolerance as measured by the occurrence of symptoms. In a large survey of compressed-air workers such a relationship was shown by Paton and Walder (1954), but the rise of susceptibility was only detectable at an age of about forty years.

In 1941, the analysis of data obtained at Farnborough showed a tendency to increasing susceptibility to subatmospheric decompression sickness with age of the order of three-fold as between the groups 19-25 and 40-45 years, but the numbers were relatively small. War-time selection and training procedures in the United States and Canada produced unequivocal evidence, for each of the six series analysed by Gray (1951) showed a steadily increasing incidence of symptoms with advancing age, even within the range 18-25 years. These figures expressed as percentages of the extrapolated incidence at age 23 have been plotted graphically by Gray, whose figure is reproduced as Figure 6-5.

Gray commented that the only reliable data showing an effect of age were those for forced descent and in most of the series he cited the test was of such severity as to cause withdrawal of a considerable proportion of the subjects. Motley, Chinn and Odell (1945) found a much less striking variation with age than some authors, particularly in the category of what we could call mild and moderate bends.

Could it be that the effect of age on bends susceptibility is slight and that the high correlation shown by Gray is in fact for other symptoms liable to cause forced descent?

Our subjects for the 28,000 foot test had a higher mean age than any of Gray's collected series. The distribution of ages was bimodal with a peak corresponding to a larger population of aircrew candidates and trainees entering under National Service and Short Service schemes and a second peak representing the more senior aircrew on long-term engagements, who were being screened for service with squadrons of Bomber Command.

An analysis of the results of tests, one or two per man, by age group yields Table 6-6.

Analysis by chi-square shows that susceptibility is significantly different from the mean in all groups at a level of probability of p = 0.001.

These data could be criticised on grounds of bias owing to the inclusion of some 330 persons having one run without symptoms and not reporting for a second test. If they were all in the youngest group they would clearly influence the analysis. Therefore a second grouping was made of the results of those who either had two runs or had symptoms on their first run sufficiently severe to preclude a second exposure. The figures (Table 6-7) show an identical trend, also highly significant on statistical test.

Table 6-6   Age versus susceptibility, all runs

Age group	Number	Number with symptoms	Expected* number	% Susceptible
17-20	642	9	36	1.4
21-23	600	17	33	2.8
24-26	482	37	26	7.7
27-29	296	32	17	10.8
30-35	385	31	21	8.1
36+	230	20	13	8.7
	2,635	146	146	Mean susceptibility 5.5%

* Calculated on the basis of an assumed uniform distribution.

Table 6-7   Age versus susceptibility, paired runs only

Age group	Number	Number with symptoms	Expected number	% Susceptible
17-20	579	9	37	1.6
21-23	535	17	34	3.2
24-26	416	37	26	8.9
27-29	247	32	16	13.0
30-35	333	31	21	9.3
36+	194	20	12	10.3
	2,304	146	146	Mean susceptibility 6.3%

Table 6-8   Age versus susceptibility, first runs only

Age group	Number	Number with symptoms	Expected number	% Susceptible
17-20	642	5	23	0.8
21-23	600	10	22	1.7
24-26	482	24	18	5.0
27-29	296	22	11	7.4
30-35	385	23	14	6.0
36+	230	12	8	5.2
	2,635	96	96	Mean susceptibility 3.7%

Again criticism may be levelled at these figures because they refer to pairs of runs. Should there be a high symptom rate in the older men when re-exposed, for example, the figures could give a false impression of the result of a single test. Therefore a third analysis was made, of the results of first tests only. The figures are given in Table 6-8.

Yet again there is a most remarkable and highly significant increase in susceptibility with age, even in the youngest groups.

Few conditions can show a relationship to age of this degree. There is an approximately nine-fold increase in liability to experience symptoms between the ages 17-20 and 27-29.

Can one find an explanation of this finding? At times the suggestion has been made that there may be a factor of repeated exposure enhancing susceptibility. That this is not so is clearly shown by a quite high incidence among those of relatively advanced years being exposed to altitude for the first time. Another possibility is that there is some other factor which has singled out a particular group of persons of the same 'vintage', a question of cohort susceptibility.

It would be interesting to discover how the trend with age affected the under seventeen group and the very elderly. Unfortunately no tests have been reported on either class.

Sex

Very few women have been subjected to decompression tests, although apparently some were employed by the U.S. Army Air Corps as decompression chamber attendants (Allan, 1945).

At Farnborough, a number of female flight test observers were exposed to altitude during the period when the writer supervised decompression testing. Neither undue susceptibility nor resistance was noticed.

Exercise

The first recorded observation concerning the effects of exertion on bends susceptibility is that of Pezzi (1937) quoted in Chapter 2, when he wrote of the association of pain in limbs with the stress of maintaining a force on aircraft controls.

During the 1939-45 war in the United States many series of studies were performed on the influence of exercise on susceptibility. Cook summarised most of these investigations in a chapter in Fulton (1951). The performance of stepping motions, weight lifting, push-ups, deep knee bends etc. all showed both a raised incidence of symptoms and a lower threshold in terms of altitude.

The writer has sought in the American literature series of tests of two hours' exposure in which exercise was performed at various altitudes in order to compare the results with those for a similar period at rest. Unfortunately no British studies on groups included exertion. The results of tests involving muscular activity are shown in Figure 6-6, which is comparable with Figure 5-3. When the best-fit curve is examined, it is found again to be an expression of a quadratic equation. Superimposition of the two curves (Fig. 6-7) shows the marked raising of the probability of the occurrence of symptoms with exercise. The overall effect is equivalent to raising the altitude by some 3,000 - 5,000 feet.
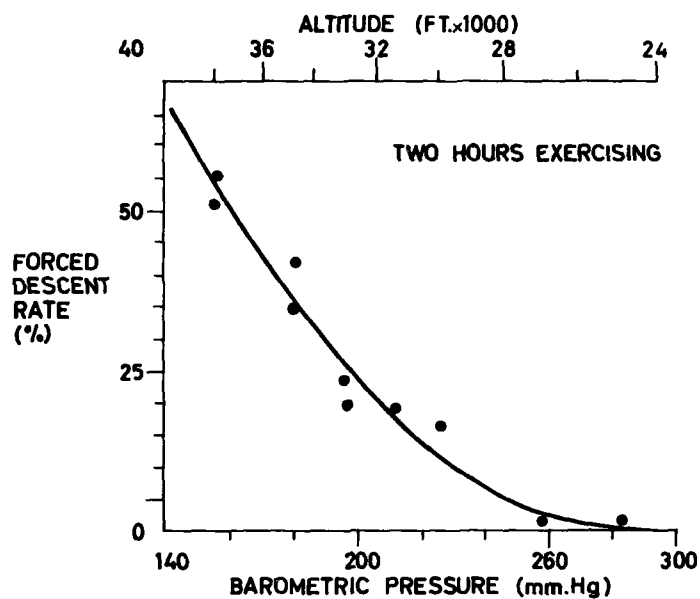
Fig. 6-6   Altitude/incidence of forced descents for 2-hour periods,
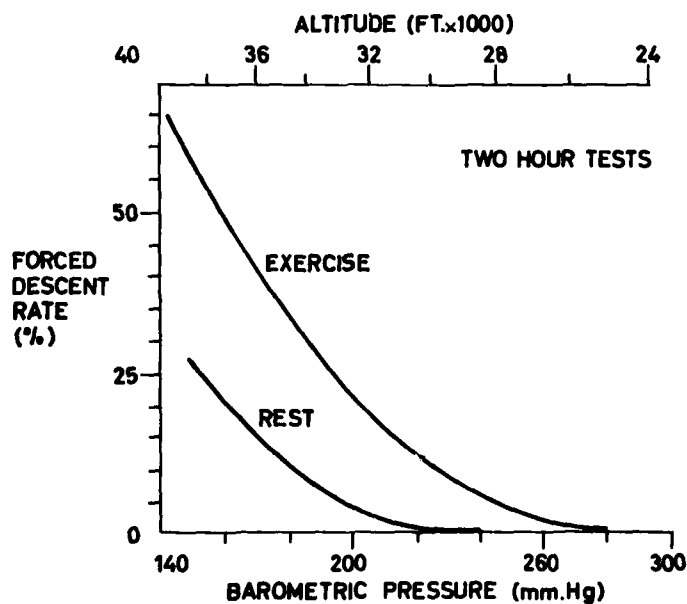exercising.

Fig. 6-7   Comparison of incidence at rest and exercising.

Ferris and Engel (1951) noted that the site of bends pain was often that subject to the maximum stress of exercise. Corroborative evidence of this has been common in the writer's experience. For example one subject of a test insisted on playing cards at altitude; he developed severe bends in the wrists and hands, not commonly affected sites (Case 15, see page 127). During exercise at altitude on a cycle ergometer, pain in the knees is quite common. Similarly, manipulation of heavy steel doors of decompression chambers often induces bends in the shoulders.

Fitness

As Gray pointed out in 1951, " it has also been a popular notion that physical fitness is related inversely to susceptibility to decompression sickness". The only reported investigation of this factor, by Karpovich (1944), proved entirely negative.

Aside from the rather poorly defined concept of fitness in terms of ability to support exertion, there are certain aspects of wellbeing or lack thereof which merit examination. These include intercurrent illness, immunisation reactions, post-alcoholic states and certain disease diatheses.

It is generally assumed that a person who is incubating or suffering from the active stages of some mild disease will react badly to altitude, just as exercise tolerance is reduced in such states. Certainly those in charge of decompression chambers are generally not willing to test persons declaring any such illness. Swann and Rosenthal (1942) appear to be the only investigators who examined this factor with any care. Before submitting personnel to altitude tests they asked them to answer a questionnaire by encircling any of the following terms which were relevant: "Average; below average; cold; sore throat; headache; constipation; diarrhoea; other". They examined the data for 3,677 man flights for correlation with the incidence of symptoms and found only a slight positive correlation between unfitness and mild bends and a negative correlation between unfitness and more severe symptoms. More detailed analysis revealed a slight possible positive relationship between headache and sore throat and the occurrence of severe bends. Balke and Wells (1958) studied the effect of physical conditioning on altitude tolerance but only in the context of hypoxia.

The writer has seen only one case in which fitness appears to have been involved.

Case 8

An officer was referred for an opinion concerning his severe reaction to a decompression test at 28,000 feet. He developed severe bends pain in a leg and shoulder, he had pain in the chest, abdominal discomfort and, whilst being transferred to a lock for descent, he experienced symptoms of chokes. On examination a few weeks later he gave a history of decreasing exercise tolerance over two years and had a generally 'weedy' appearance; pale, with a poorly developed physique, a lax abdominal wall and pot-belly, and an air of lassitude. He admitted to smoking some 30-40 cigarettes daily and a consumption of 6-9 pints of beer daily. After clinical examination had failed to reveal any specific defect he was persuaded to reduce to a very low level his consumption of tobacco and alcohol, and he was given an intensive course of physical exercise. When he was re-tested at altitude some months later, he passed without symptoms.

Temporary post-alcoholic state can have a decidedly adverse effect on resistance to altitude. Several cases have been seen in which severe reaction was associated with such a hang-over and re-testing in a more normal physiological state has been without incident. The best example follows:

Case 9

> A young and generally fit Flight Cadet was referred for consultation. He had
> passed the first of 2 decompression tests of 2 hours at 28,000 feet with no
> more than very mild general itching, but a few days later produced a quite remark-
> ably severe attack of bends in the right knee and ankle after 80 minutes at the
> same height: as a consequence he had to be removed from the chamber. A gen-
> eral enquiry about health and habits drew only an admission of very mild and ir-
> regular drinking of alcohol, but subsequently he confessed to having consumed 12
> "rum and colas" the night before the test! This resulted in what could be con-
> sidered as a pharmacological conflict, since this mixture contained enough alcohol
> to induce considerable depression but the total quantity of caffeine in the 'cola'
> component was enough to bring about excitation and suppress sleep. The victim
> suffered alternate bouts of profound sleep and sleeplessness, punctuated by vomi-
> ting and later the anticipated anorexia. Re-testing without such 'pre-medication'
> resulted in quite symptom-free ascents.

Local inflammatory processes and generalised reaction to antigen may have a tem-
porary influence on susceptibility. The writer has seen a case of severe headache,
visual disturbance and impending collapse in a man tested at altitude a few days
after vaccination, which was accompanied by quite marked general malaise. A
repeat test some weeks later was without incident. Carey in 1958 reported a case
of severe bends pain, blurred vision, dizziness and nausea in a pilot flying at a
cabin altitude of 28,000 feet, six days after a poliomyelitis vaccination with killed
virus. The inoculation and the bends pain were in the same arm. Strangely,
however, ascent to 37,000 feet the following day was tolerated without development
of any symptoms. Clearly these two cases do not permit generalisation, but it is
recommended that exposure to altitude during the active stage of antibody production,
when malaise and low grade fever are common, should be avoided.

During the analysis of incidents affecting 141 persons during 28,000 foot decom-
pression tests, the opportunity was taken to scrutinise their documents for evidence
of allergic conditions. This was prompted by an observation that several in-flight
cases seen earlier had histories of personal or family occurrences of allergic con-
ditions. Of the 141 aircrew, nine (6.4%) had histories of allergy: six had hay fever,
one chronic urticaria, one sensitivity to penicillin and one childhood asthma. This
incidence would appear high for aircrew who undergo very stringent selection medi-
cal examination, but it does not seem possible to find a base-line morbidity for
allergic conditions in aircrew.

There appears to be only one parallel observation on a possible relationship between
allergy and susceptibility. Gusinskii and Shvarev (1964) described severe spinal
paralysis occurring in a diver, who fortunately made a very remarkable, although
incomplete, recovery. They concluded that his undue susceptibility compared with
colleagues subjected to an identical dive and the marked reversal of the spinal
lesion, were to be associated with oedema at the site of spinal cord embolism and
that the oedema itself was associated with abnormal vascular reactivity in view of
his long history of urticaria, mild idiopathic oedema and joint pains.

Injury

Gray (1951) reviewed the three available papers in which a relationship between
injury and susceptibility had been sought and reached the conclusion that no positive
correlation existed. There is, however, a natural tendency for individuals to
blame the occurrence of bends pain on a pre-existing lesion. It is important to
know whether any such association does exist, either generally or for specific types
of injury, for the purpose of assessing the potential relevance of such injury in air-
crew.

It is a common trap to ask a person who has experienced bends whether the affected site has ever been injured. Almost as often as not a positive association will be claimed. It has been the writer's teaching and practice for many years to enquire about "sprains, strains, fractures, dislocations, swelling or other injury" before submitting a person to a decompression test. In following this practice it becomes clear that, with one exception noted below, a history of injury does not predispose to bends.

Special cases are those of very serious injury or operative interference in which grossly distorted anatomy may be thought of potential significance. The writer has seen and examined cases of repair by metal plates and screws in the femur, grossly misaligned fractures of humeri due to gun-shot wounds and a case of recently resolved chronic ostemyelitis in which altitude exposure produced no symptoms of any sort. This is in distinct contrast to the case of foot pain in a site of aseptic necrosis of a tarsal bone reported by Allan in 1945.

Of 147 persons found to report symptoms in the very large series exposed to 28,000 feet equivalent for two hours (see Appendix) six claimed that pain was felt at the site of an old injury. It was felt wise to examine the history of those affected for traumatic incidents. Each man's documents were examined with care for a mention of bony or soft tissue injury either before or during military service. The lesions were classified according to site and it was found that there were twenty-four loci of fracture or dislocation in the upper limbs (including the clavicle), one arthrotomy of the elbow for loose bodies and twenty-five lesions of the bones or joints of the lower limbs.

Not one of the upper limb lesions was the source of pain; a striking negative finding.

One man had pain on two separate occasions in an ankle which had been the site of a compound fracture seven years earlier. Twelve individuals had histories of knee-joint injury; tears of the menisci, haemarthrosis, ruptured ligaments or loose bodies (one bilateral) and five of these had had fully satisfactory surgical correction of their injuries. The bilateral case experienced pain in both knees at altitude and four other men had pain in their 'bad' knees. Two of these had had effective arthrotomy six and fifteen years earlier.

The occurrence of pain in five of thirteen knees known to have been the site of internal disorder is in striking contrast to the lack of association between trauma and susceptibility in the upper limb cases. Apart from those enumerated above, several cases of knee pain many years after an effusion-producing injury have been seen and Griffiths (personal communication) has seen a similar relationship in a compressed-air worker.

Body Build

The question of a physique characteristic of high susceptibility to decompression sickness is one which has occupied many clinicians and research workers. Many of the early compressed air workers were impressed by obesity and plethoric build as being associated with high risk. For example, Smith (1873) in the first monograph published on the subject stated that "After the work in the New York caisson had been some months in progress it was observed that there was a preponderance of stout, heavily built men among those taken sick". On a purely practical topic, a commercial Diving Manual (Siebe Gorman & Co., 1886) recommended to employers, in the absence of medical advice, "do not employ: 1) Men with short necks, full-blooded and florid complexions." Some advice was contradictory, as in the case of Levy (1922) who stated that obesity was not related to undue susceptibility, but nevertheless advised against employment of 'corpulent' workers!

AD-A111 509   ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT--ETC F/G 6/19
SUBATMOSPHERIC DECOMPRESSION SICKNESS IN MAN. (U)
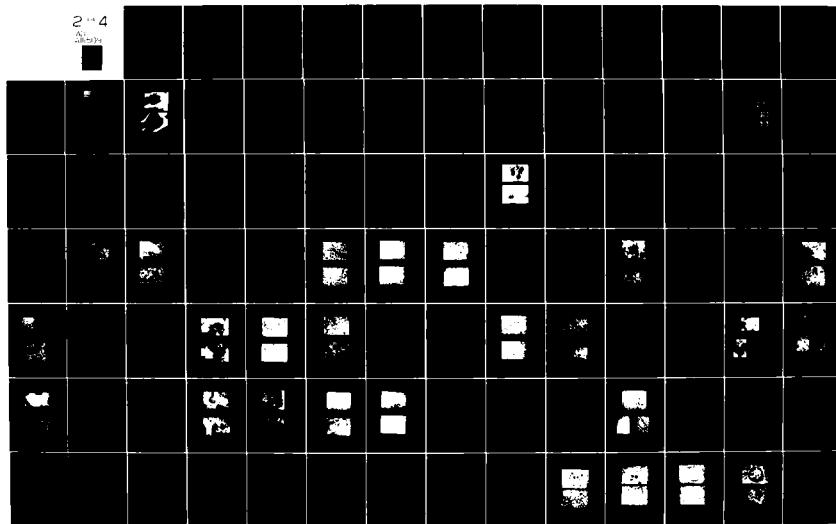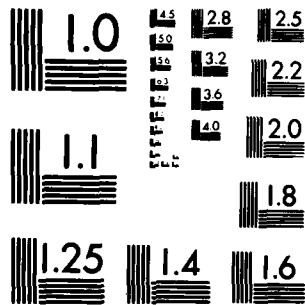APR 69   D I FRYER
UNCLASSIFIED   AGARD-OGRAPH-125   NL

2 ⁻⁴ 4

1.0

1.1

1.25 1.4 1.6

2.8 2.5

3.2 2.2

3.6

4.0 2.0

1.8

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Scientific interest was really initiated by Vernon (1907) who showed experimentally that nitrogen is at least five times more soluble in oils and fats than in aqueous media. Boycott and Damant (1908A) studied the mortality of rats and guinea pigs subjected to decompression in relation to their body composition and revealed a direct correlation between fat content and susceptibility. Many other authors have shown such a relationship in animals; Gowdey and Philp (1965) using rats, Viotti and Walder (1965) comparing obese and starved guinea pigs and Antopol et al (1964) studying genetically obese and hyperglycaemic mice.

Many series of wartime altitude decompression tests have shown a relationship between weight and susceptibility. For example, Swann and Rosenthal (1944) showed a direct relationship in their 3,168 man/flights as did Motley et al (1945) in their much larger series (Fig. 6-8).

Much more relevant is the degree of obesity. This is often expressed as weight relative to actuarial age/height/weight tables, but these reflect only the average of a large group. The fact that as age increases, so does permissible weight, must reflect an increase in adipose tissue in the average population, as muscle and skeletal bulk can hardly be expected to increase with age after early adult life. Behnke was one of the first to point out, in 1942, that many men of distinctly muscular build such as athletes, boxers and, in particular, American-football players may be so overweight by such standards as to be unacceptable for military service and yet are, even to a most cursory examination, in no way obese.

The most striking and relevant recent evidence on the unreliability of actuarial data in assessing obesity comes from Wamsley and Roberts (1963). They examined USAF flying personnel and on age/height/weight tables assessed those more than 20% above their standard as overweight. They measured obesity by total body water measurement. On their analysis the number of obese and non-obese on this criterion were divided as follows:

Table 6-9   USAF Flying Personnel build. (Derived from data of Wamsley and Robers, 1963)

Overweight	Obese	5
	Not obese	6
Not overweight	Obese	15
	Not obese	25

Put in another way, fifteen of twenty obese persons were not overweight and six of eleven overweight persons were not obese!

Many indices of build have been examined in this context. Linear density (weight/height) was used most commonly in the 1940s; Gray (1951) gathered data from many sources and showed a remarkably consistent relationship (Fig. 6-9). Others used ponderal index (weight/height^3),surface area etc.

Body specific gravity, difficult to measure, is probably the best index of fat/lean ratio, but no large series of decompression subjects has been examined in this way. Fraser in 1942, found a correlation between incidence and obesity as measured by body specific gravity in his series of forty-four subjects. The writer has used skin-fold thickness in a small group but the numbers were insufficient to allow any conclusions to be drawn from an apparent trend towards a direct relationship.
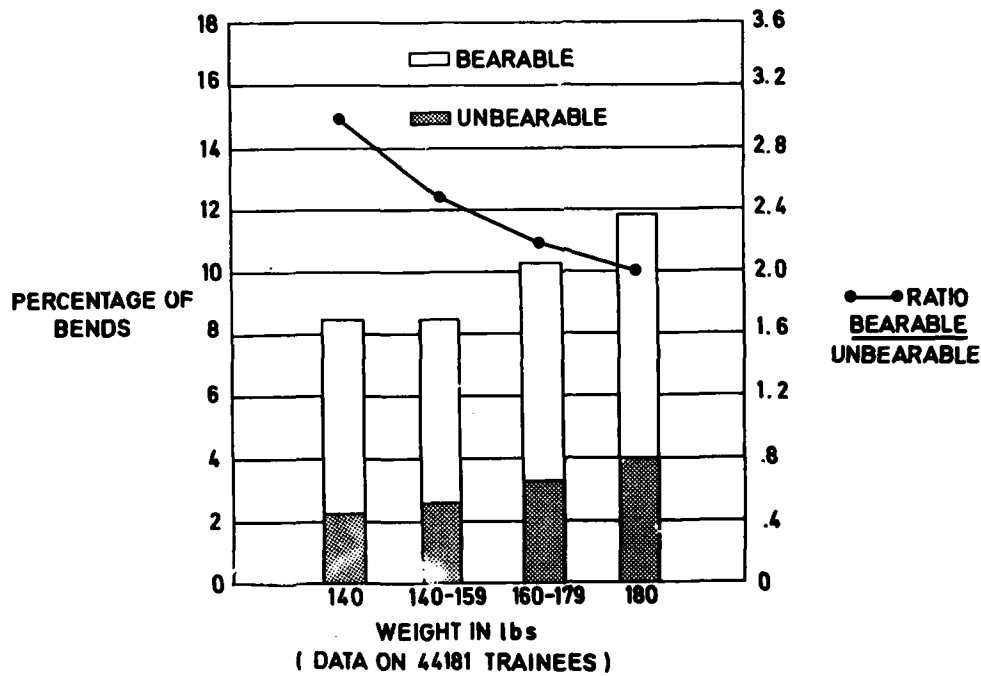
Fig. 6-8   Incidence of bends of two grades of severity related to
body weight (Motley, Chinn and Odell, 1945).
Reproduced by permission of the Aerospace Medical
Association.

REL. SUSCEPT=122 (LIN. DENS.)-177
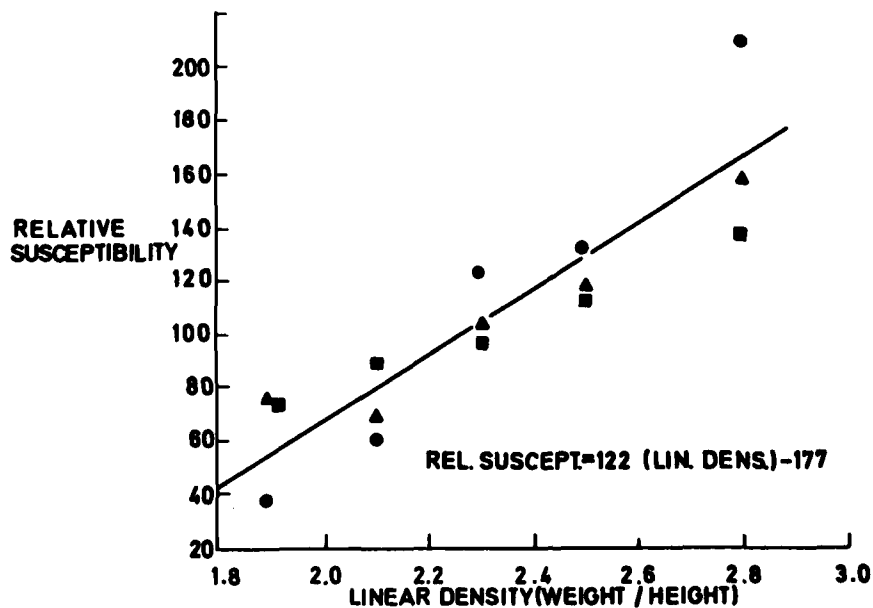
Fig. 6-9   Susceptibility to decompression sickness related to linear
density (Gray, 1951).

In the author's large series of men tested at 28,000 feet, referred to elsewhere in this work, height data were not available for the majority of subjects. The expected relationship to crude weight was apparent in these men, however.

Table 6-10   Relationship between weight and susceptibility in 28,000 ft two hour test

Clothed weight	Number	Number with symptoms	% Susceptible
Under 160 lb	1021	42	4.1
161-174 lb	572	48	8.4
175 lb and over	600	49	8.2
	2193	139 Mean	6.3%

Somewhat surprisingly in the compressed-air field such a correlation has rarely, if ever, been demonstrated.   In a series of 141, Paton and Walder (1954) could find no correlation between weight and bends incidence.   Wise (1963) looked at data for 413 divers who had reported symptoms and found a similar lack of association. However, he found a positive correlation at the 1% level between bends occurrence and Sheldon somatotype index.   Walder (1966B) looked for a relationship between skin-fold thickness and bends incidence in workers at the Tyne tunnel but again was unsuccessful.

Cotes and Gronow (1952) initiated an interesting line of investigation.   They studied the symptoms experienced by a group subjected to a decompression test comprising two-hour exposures to 37,.000 feet.   They concluded that an overweight state predisposed not only to symptoms, but particularly to the more severe manifestations such as chokes and collapse.   McNutt (1943) has suggested a similar relationship, although he produced no numerical evidence.

In the survey by the writer of the 28,000 ft test subjects, the opportunity was taken to examine the hypothesis that the positive relationship between weight and overall incidence of decompression sickness might be due to a higher incidence of certain symptom complexes in the overweight, rather than a uniform trend for all symptoms.   As has been stated earlier, height data was not available for all subjects (almost 3,000), but stature was ascertained for all those who complained of symptoms (147 in all).

The results are shown in Table 6-11.

Table 6-11   Age/Weight Data for symptom-sufferers

Group	Number	Mean degree of overweight	Mean age	Mean weight
All subjects	2656	Not known	25.35 yr	164.6 lb (clothed)
All with symptoms	147	+ 14.75 lb	28.37 yr	-
Chokes	9	+ 19.44 lb	32.44 yr	-
Secondary collapse	17	+ 13.29 lb	30.96 yr	-

It can be seen from the examination of the two groups deemed large enough to diff-
erentiate from the bends group that there is no detectable relationship between
degree of overweight and collapse and only a slight possible trend in the chokes
cases.   The age trend is much more suggestive.

The question of build or diathesis has already been alluded to.   Could there be a
characteristic which determines both susceptibility to overweightness and suscep-
tibility to decompression sickness ?   No answer is available (the body type as-
sociated by many with post-descent manifestation will be dealt with elsewhere).
However there is a hitherto unpublished observation which is surely germane.

In spite of very vigorous attempts in US, Canadian and British forces to reduce the
incidence of obesity, there are no reports of any effects on susceptibility to the
effects of altitude, even though one of the aims in air forces has been to diminish
altitude sensitivity.

Two such cases have been seen and investigated by the writer.

Case 10

In April 1959, a pilot was subjected to a decompression test of 2 hours at 28,000
feet on two occasions.   On the first, on 27th April, he experienced mild bends
but did not need to descend prematurely.   He noticed after descent mild subcut-
aneous tenderness over the chest and belly.   On 29th April, in the course of the
second test, he developed primary nondepressor collapse accompanied by neurolo-
gical symptoms which were, unfortunately, not very fully described but included
weakness and numbness of the right leg.   Examination by a consultant physician
revealed no underlying illness, but for his age (34 yr) and height (72 in) he was
considered at 213 lb to be some 35 lb overweight.   He was therefore encouraged
to reduce drastically his carbohydrate intake, care being taken to maintain his
vitamin, mineral and protein consumption.   He was seen on 29th September, 1959,
having stabilised at a weight 39 lb less than his previous level.   He appeared and
claimed to feel very much fitter than before.   He was re-tested, accompanied by
the writer, following an identical time and height profile to that in his earlier tests.
After 15 minutes he developed slight bends in the left shoulder; at 26 minutes he
had pain in the other shoulder also; at 43 minutes he developed scintillating scot-
omata and saw zig-zag patterns of light.   He became very flushed, anxious and
his pulse became very rapid.   He felt faint, in spite of his high colour.   A rapid
descent was initiated immediately; the symptoms cleared quickly but for persis-
tent tachycardia and visual disturbance which became a left homonymous blurring.
He later developed a left-sided headache.

The most striking feature of this case was the similarity of syndromes in the second
test before weight reduction and that five months later.   In particular, the non-
depressor type of collapse is extremely uncommon, but occurred on both occasions.

Case 11

A flight engineer was decompressed twice in August 1960 and during his second run
he experienced throat irritation, itching, mottling and tenderness of the skin of his
arms and chest after one hour at 28,000 feet.

He, too, reduced his weight by dieting on a similar regime to that of the previous
case.   Having attained, by the loss of 33 lb, a satisfactory weight of 165 lb for his
age (37 yr) and height (66½ in) he was sent to the writer for re-examination.
He was taken to 28,000 feet for 2 hours on 9th December, 1960, without incident.
On 12th December he was again decompressed to this simulated altitude.   After

28 minutes he complained of bends pain in the left arm and 10 minutes later he
developed a similar pain in the opposite arm. After 98 minutes he quite suddenly
developed a general hot feeling, malaise and was dazed. He was brought to ground
level as rapidly as possible, with a marked improvement but he was warm and
flushed in quite cool surroundings. His pulse at the wrist was slow and regular
(64 per minute) but surprisingly thin for a blood pressure of 120/80 by auscultation
at the elbow. When his shirt was opened he was found to have bright red erythema-
tous blotches on the chest, the shoulders and on the inner aspects of both upper arms.
These faded slowly over several hours. He volunteered that the symptoms and
signs were very similar to those experienced in his pre-slimming incident.

The outcome in both these cases was not merely a retention of sensitivity, but the
recurrence of very similar symptoms after weight reduction. Neither case was
purely subjective: the first showed marked tachycardia and flushing; the second
had classical mottling. It is clear that reduction of the mass of adipose tissue does
not, in these two examples at least, alter susceptibility. As has been mentioned
above, no comparable cases are recorded in the literature. At various interna-
tional meetings the writer has enquired among colleagues, including those from
the United States, where the most vigorous weight reduction programmes had been
instituted, but no re-testing after slimming could be recalled. De Vries, of the
Royal Netherlands Air Force, in 1962 (personal communication) recollected that
one man of high susceptibility had undertaken weight reduction with similar negative
result but one year later he was found to be resistant. The suggestion was made
that some alteration in tissue elasticity may have occurred in the intervening period.

The whole question of obesity in relationship to susceptibility to illness of any sort
is one which leads to emotional outbursts and almost irrational argument on the part
of many authors. Powell, Carrigan and Stanfield (1963) contributed an article in
which, whilst challenging others they fell into the very pitfalls they were attempting
to point out.

Hypoxia

Motley et al (1945) made a most interesting comparison between those personnel
subjected to hypoxia as a part of a decompression test and their colleagues who were
exposed to an identical pressure profile but without hypoxia (i.e. subjects versus
observers). There was no difference in the overall incidence of bends, but a
slightly smaller proportion of severe as opposed to mild pains in the subjects.

No other comparable survey is known, but the results are at variance with common
experience in research. It is generally felt that during experiments in which pro-
found hypoxia is induced, bends pain is surprisingly common. This is particularly
noticeable in studies of simulated parachute escape or experiments on marginally
adequate oxygen systems. The writer has personal experience of both circum-
stances and has also a report from a colleague whose only experience of bends was
in a hip (a rare site) when moving around in a decompression chamber, wearing a
passenger-type disposable continuous flow oxygen mask, not designed for use by a
person carrying out such considerable physical activity.

The apparent paradox between the Motley et al findings and the admittedly unsup-
ported but strong impressions of the author, is probably quite simply explained.
The war-time US series comprised people deprived of oxygen during ascent, un-
til they showed signs of imminent collapse, generally at 26,000 to 30,000 feet, when
their oxygen supplies were connected and the run continued to complete one hour at
30,000 feet, followed by fifteen minutes at 38,000 feet. Thus the hypoxia was brief,
early and generally at altitudes well below 30,000 feet. The real meaning of the
survey results is that initial hypoxia does not increase the incidence of bends during
subsequent exposure to altitude with adequate oxygenation.

The circumstances in which the writer and his colleagues have sensed an increase of susceptibility are those of induced fairly long-term supportable levels of hypoxia during the course of an exposure to a time/height profile likely to cause a definite but lower incidence of symptoms than that actually observed.

Previous Exposure

On this topic, again, there is a wealth of unrecorded observation and comment, but virtually no written evidence.

Symptom Recurrence - If a person is exposed to altitude until bends pain develops and he is then restored to ground level, subsequent re-ascent within a few hours, will lead to recurrence of symptoms in the same site within a very short time; indeed, often during the ascent. Ferris and Engel (1951) considered that re-ascent caused recurrence if carried out within four to six hours. Rodbard (1944) carried out the only published study on this subject. His results are shown in Table 6-12. It will be seen that there is almost a certainty of recrudescence of symptoms following repetition of decompression within three hours.

Table 6-12   Recurrence of bends on reascent (data of Rodbard)

Interval between ascents	Number exposed	Proportion recurring
0-20 min.	5	100%
21-60	52	50%
61-120	52	52%
121-180	13	38%
181-1800	27	0

In experiments in which the writer has taken part, it has seemed probable that enhanced susceptibility has been more extended than Rodbard's evidence would suggest.

A deliberate attempt to assess the effect of daily exposure was made at Farnborough in 1941 (Flying Personnel Research Committee, Report 267). The data do not suggest that there was any tendency for symptoms to recur on the day following their first occurrence. In any case it has always been the practice of the Royal Air Force and of the Royal Navy to separate decompression tests by a minimum of forty-eight hours. This implies a considerable safety factor over the probable time minimum for avoidance of recurrence.

The recurrence hazard is highly significant in aviation practice.

Two examples spring to mind.

Case 12

> An RAF navigator in the course of a cross country flight in a two-seat jet aircraft in Canada in 1954, developed tightness and pain in the chest, with mild inspiratory discomfort. The cause of the symptoms was not appreciated even when they improved almost to the point of full recovery on landing. The pilot and navigator decided that it would be wise to refuel and take-off for the second leg of their flight before the latter "felt ill again". On reascent the symptoms developed again very rapidly and were much more severe, with marked post-descent shock.

Case 13

> A pilot. instructing on unpressurised trainer aircraft. had noticed over a period of months an increasing tendency to develop mild bends. One evening he was instructing at 30,000 feet when. after 5 minutes. he developed mild pain in an elbow which was relieved during descent and disappeared before 10,000 feet was reached. One and a quarter hours later he took off on a second flight. The pain recurred with increased severity on passing 26,000 feet and at 27,500 feet became incapacitating. He also developed severe chokes. with paroxysmal coughing of sufficient intensity to preclude completely communication with the pupil except by hand signals.

Asymptomatic Previous Exposure to the Same Altitude - The writer has repeatedly observed that whereas symptoms are normally experienced in a particular site after approximately fifteen minutes at a given altitude, they will occur within a much shorter time if he has undertaken several short duration exposures earlier in the day. This is an observation common among experimenters and one of considerable importance in flying.

For example, when a long distance flight by a display team of a number of training aircraft was being planned, it was realised that a potential hazard was involved in that the multiple stages of the flight in these unpressurised aircraft would be separated by very short intervals for refuelling. Testing of the crews, who were quite without history of bends in flight in this particular type, gave very striking results. None developed symptoms in a simulation of one stage. Several experienced very severe symptoms indeed when the exposure was repeated about two hours later. Even when these men were eliminated, the actual outward flight was marked by a precautionary landing by one aircraft following the occurrence of bends in a pilot on the third leg of the journey and several milder in-flight incidents.

No figures are available for the actual relative influence of prolonged single and multiple repeated exposures. Clearly it would be an enormous undertaking to attempt to estimate effects of variation of the interval between exposures and the actual lengths of individual exposures. It is sufficient in practice to assume that repeated exposure within three hours of descent may be considered simply additive e.g. one hour at altitude, two hours at ground level, followed by a further hour at altitude is equivalent to two hours straight. Lengthening the interval reduces the cumulative effect until, at about twelve hours, exposures may be regarded as separate events.

'Silent Bubbles' - It is conceivable that bubbles might form and reach a stable state in such quantities and individual size as to be asymptomatic. Subsequent reduction in ambient pressure could lead to immediate increase in size, beyond the threshold for nerve fibre pain-ending stimulation. This situation has been aptly called that of 'silent bubbles'.

There is good evidence of such a condition. For example, the writer was conducting a series of experiments on pre-oxygenation (see Chapter 10). When the oxygen breathing was at 8,000 feet, protection was almost complete. When the first sojourn was at 25,000 feet, not only did cases arise commonly on the 40,000 feet test, but many occurred during the ascent. From earlier work and from comparison with the time of onset of symptoms on direct ascent from 8,000 feet in the same men, it is clear that they were conditioned to a heightened level of potential susceptibility at 25,000 feet.

Marbarger et al (1956) conducted rather similar trials and the effectiveness of pre-oxygenation at 22,000 feet was strikingly lower (78.8% pain free in two hours at 38,000 feet) than at 18,000 feet (90.9%) or 15,000 feet (84.9%). Damato et al

(1963) showed a remarkably high incidence of symptoms arising very rapidly during and shortly after ascent to 33,750 feet after twelve hours stay at 18,000 feet breathing 50:50 O_2 and N_2.

Prior Supersaturation - It has already been pointed out that sojourn at lower pressure than standard sea level offers some protection presumably by reducing the total body inert gas content. It is theoretically possible that raised body inert gas content can lead to an alteration in susceptibility at altitude.

Newton Harvey (in Fulton, 1951) referred to unpublished work by McElroy and Whiteley in which cats were taken from supra- to subatmospheric pressure with development of bubbles in the blood. McIver and Leveritt (1963) used a similar regime for many of their dog experiments and Gramenitskii and Savitch (1964A) in Russia, Gowdey and Philp (1965) in Canada and Furry, Reeves and Beckman (1966) in the USA have all exploited this supra- to subatmospheric pressure range technique.

What of the risks to man? Snyder and Duffner in 1958 attempted to assess the efficacy of diving schedules by a deliberately provocative ascent to altitude shortly after surfacing. This was used for some time (Kiessling and Duffner, 1960), but fell into disuse because of the severity of some of the cases. Here it seems very probable that silent bubbles were involved.

A surprisingly slight ascent can provoke symptoms. For example, after completing some prolonged and very deep dives, a team of Royal Navy personnel went ashore on one of the Canary Islands, only to find several of their number afflicted with bends in a bus whilst traversing a mountain pass some 8,000 feet above sea level! (Hempleman, personal communication).

A co-pilot of an RAF V-bomber (Case 13, earlier in his career) was very surprised to find himself suffering from bends pain in his arm at a cabin altitude of 8,000 feet: he had been diving in the Mediterranean to a depth of 140 ft, using an Aqualung some twelve hours earlier.

Preston (personal communication) tells of an incident in an airliner on a scheduled service. A 45 year old passenger complained of pain in his chest and became grey, dyspnoeic and collapsed during a flight over the Alps at which time the cabin altitude was 5,000 feet. The captain of the aircraft was, fortunately, a keen amateur diver and on interrogating the ill man he discovered that he was a sponge-diver from the town of Kyrenia in Cyprus who had been diving in 'Standard' dress at 120 feet for thirty minutes on the day before the flight. The aircraft was diverted to land at Geneva and the patient was rushed to a recompression chamber, where he made a rapid and complete recovery.

'Acclimatisation'

One of the most remarkable findings of those in charge of compressed air work has been the clear evidence of 'acclimatisation' (Walder, 1966A). Over a period of years it has become apparent that men working in hyperbaric conditions develop bends less and less frequently as they continue with daily exposure. An interval of a few days negates the acclimatisation. Most oddly, it seems that an increase of pressure at the work face causes the population to revert to high susceptibility again until some days have passed and the men have become accustomed to the new pressure level. A similar acclimatisation has been claimed to occur in dogs (Aver'yanov, 1964). Does such a process occur in aviators?

In 1941, a single subject seemed to show such an acclimatisation with daily ascents for one week, followed by a week's break, then another week of ascents and so forth for several weeks. Similarly three men were subjected to four daily runs for eight days, showing a fall-off of susceptibility (RAF, 1941). No other experimental group appears to have undertaken similar studies. The only relevant report in recent years has been that of Hall (1955B). Unlike the Farnborough workers he observed, in the case of a single subject decompressed to 35,000 to 43,000 feet on 142 occasions, that the incidence and severity of symptoms rose and that the degree of descent necessary to ease symptoms simultaneously increased with repetition.

There thus appears to be no clear-cut answer to the question posed above. To ascertain the answer would require a very prolonged programme of human experimentation which few, if any, would wish to undertake.

Hydration

Cook (1951) reported work of others on hydration and susceptibility. The results were utterly confusing. Thus, one group found a high inverse correlation between daily water intake and susceptibility in a large group whereas a Canadian group found no reduction in incidence in a number of subjects who, after establishing their normal susceptibility, doubled their fluid intake. Walder (1947 and 1948) appeared to demonstrate quite clearly a correlation between serum surface tension and resistance to the effects of altitude in man. He not only showed that a high static surface tension was associated with low susceptibility, but could apparently reduce the incidence of bends when the surface tension of subject's serum was temporarily raised by the ingestion of isotonic saline.

Psychological Influences

As has been stressed earlier, the vast majority of evidence for the occurrence of decompression sickness is subjective. As such, it is distinctly possible that a significant proportion of cases might be spurious, in that symptoms could have been falsely reported for one reason or another. Conversely a number of cases may well have been concealed by persons not wishing, for some reason, to confess to susceptibility.

Many factors are relevant. Concealment might be motivated by pride, fear of downgrading, stoicism or even ignorance of the relevance of minor symptoms. False declaration might result from a wish to be excluded from certain duties, temerity, excessive attention to such minor sensations as accompany temperature changes and gut volume changes concomitant with decompression or apprehension arising from the observation of distress in others.

The latter is very important. For example, it is well known how vomiting may be precipitated by witnessing vomiting by others, how fainting occurs in batches in stressful situations and how even complex syndromes may arise in emotionally tense communities. So far as is known, no author has hitherto investigated the relevance of the emotional factor in decompression chamber tests.

If the occurrence of decompression sickness in one man has no influence on the susceptibility of other members of a group and the occupants of a decompression chamber are randomly selected from the population, the distribution of cases among 'chamber-fulls' (for the want of a better term) will be in accordance with the laws of chance. Knowing the overall rate of symptom-declaration it is possible, by the application of the binomial theorem, to calculate the frequency of occurrence of single and multiple cases in a population.

An analysis has been made for the occurrence of 164 cases in the almost 5,000 man/runs of the 28,000 foot series already referred to. In Table 6-13 will be found the actual incidence of single and multiple cases.

Table 6-13   Multiple occurrences

Number of cases reported in a single 'chamberfull'	Number of occurrences
1	106
2	16
3	7
4	0
5	1

It was not practicable to ascertain from the record cards the composition of groups tested, but it is absolutely certain that no more than ten persons could be accommodated in a chamber for any one run. Thus, for the case of ten-per-chamberfull (i.e. the case in which multiple cases are most likely) we may calculate the probability of single and multiple occurrences (Table 6-14).

Table 6-14   Calculated probability of multiple occurrences

Number affected per chamberfull of ten persons	Frequency of occurrence on chance basis	Observed frequency
0	353	Unknown
1	122	106
2	19	16
3	1.7	7
4	0.10	0
5	0.0043	1
6	0.00012	0

Examination of these data shows an excessive number of three and five-case runs, but no four-case runs against a probability of 9 to 1 against. It is not easy to interpret the data, but it would seem that multiple cases are more common than would be expected on a chance basis. If one assumed, quite reasonably, that a chamberfull comprised six persons, the discrepancy is most striking.

Before assuming that this is proof of a psychogenic factor it is essential that other causes for a similar finding should be considered. The same could result from a group factor; for example diet, weather conditions or atmospheric contamination. It is not possible to exclude any of these. More important is the suggestion that the occurrence of a case might trigger confession among others who have hitherto concealed symptoms. Keir, who supervised many such tests, has reported (personal communication, 1964) that it was common to hear in casual conversation after a test that a person had concealed the occurrence of twinges. If pride is, as one suspects, a factor in concealment, then the disclosure of one case will be a potent releaser in that a person will no longer feel ashamed to own up as he will no longer be the first to do so.

It is considered that the evidence given above is not sufficently strong to support
or yet to demolish a theory of psychogenic case occurrence in groups.   However,
it does reveal that a group factor is probable, whatever its nature might be.

Summary

Decompression sickness affects some persons more frequently than others.   Group
susceptibility also varies from time to time.

A higher overall symptom rate is to be expected in morning as opposed to afternoon
tests.

Possibly more cases will be declared if larger groups are exposed simultaneously.
Certainly older, fatter persons prove more liable to experience symptoms under
given conditions.

In otherwise constant circumstances, exercise, cold, post-alcoholic state, prior
exposure and possibly hypoxia render an individual more susceptible.

In spite of a vast number of observations, carefully and thoroughly analysed, it is
not possible to forecast with any reasonable degree of certainty the performance
of an individual at altitude in comparison with others similarly exposed except by
actual test.

7

Post – Decompression Phenomena

Persistence at Altitude

In general, symptoms persist and increase in intensity if altitude is maintained. Certainly this is so at 35,000 feet and above. At lower altitudes however it is not unknown for symptoms of a very mild degree to pass off in spite of maintenance of altitude.

So far as is known, no numerical analysis of this question has been attempted hitherto. The writer has examined the series of 147 cases observed in the 28,000 foot, two-hour test. The results are shown in Figure 7-1. The ordinate, which has a discontinuity, represents the proportion of cases of each category; the abscissa has an arbitrary scale, starting with the onset of symptoms on the left and ending with descent on the right. This period may represent a few minutes in the most severe cases or over an hour in the mildest and the descent may have been urgently indicated by symptoms or planned at the end of the test exposure.

Cases are categorised as follows:- those unabated by the time that descent was initiated; those in which the severity was decreasing, but had not diminished to an imperceptible level; those in which symptoms abated completely only to recur, either in similar form or in a different site; and finally, those in which symptoms, having arisen, disappeared in spite of maintained altitude. It can be seen that no more than 12% fell into the last category and even of it is assumed that those showing improvement might all have experienced complete recovery if the exposure had been prolonged, the total would have been no more than 15%. The great majority in these classes were very mild bends or minor itching.

It is felt that the symptoms observed at 28,000 feet are, on the whole, less severe and less dramatic in onset than at higher altitudes. It is therefore probable that the proportion of cases not progressing, once established, would be smaller were the altitude of exposure increased. Certainly severe bends, chokes, neurological disturbance and formication never remit if altitude is held.

Relief on Descent

In general, a descent of a few thousands feet will relieve bends pain and bring about a striking improvement in other cases. Rarely has the altitude at which relief is achieved been analysed. Motley et al (1945) plotted crude data from their very large series (Fig. 7-2). They admitted that the original data were probably of low accuracy, but nevertheless it is clear that 90% or so of symptoms (in their case, all bends) were relieved by a pressure rise of 180 mmHg, which corresponds to descent from 38,000 to 20,000 feet or from 32,000 to 17,500 feet.

If symptoms take a matter of minutes to resolve, the altitude decrease necessary
for relief will be over-estimated if continuous descent until relief is employed;
the over-estimation will rise with higher rates of descent. Disentanglement
of the pressure-rise and time elements in relief of symptoms is generally not
possible because of the undesirability of prolonging exposure in the presence of
severe symptoms. It is, however, commonly observed that a slow descent to
relief, followed by maintenance of the new altitude, is followed by recrudescence
at the new level.

Persistence of Symptoms after Descent

Bends

No more than two per cent of cases of bends, in the writer's experience, are
incompletely relieved by descent to ground level. When pain does persist,
it is of the nature of a dull ache, not unlike tooth-ache in character, felt deeply
in the neighbourhood of the joint. It is only slightly, if at all, affected by pos-
ture or activity.

The most persistent case seen personally arose in the author himself who, after a
particularly acute bend in a knee, had pain of quite disturbing and distracting
severity on descent and this diminished in intensity only slowly over the suc-
ceeding five hours.

Stiffness has been mentioned in the literature but has not been seen personally.
There is, however, a definite tendency to restrict the movement of a painful
joint even if the movement itself does not cause a worsening of the pain. To
this extent, therefore, mobility may be reduced voluntarily, simulating true
stiffness.

Chokes

The acute cough and discomfort of chokes are dramatically relieved by descent
and only rarely is there more than moderately severe inspiratory snatch by the
time that ground level is reached. Dyspnoea is commonly remarked upon,
but this is probably in most instances no more than the rapid breathing generally
associated with apprehension.

Skin

Itching generally disappears abruptly during descent but, as has been observed
in Chapter 3, soreness, often exquisite, commonly follows. Mottling of the
skin takes a period of from several hours to two days to disappear. Quite often
what has been a very mild blotchiness will become more marked during the first
few hours following descent.

Case 14

The most remarkable case seen by the author was that of a pilot who had a long
history of chronic urticaria. On 2 occasions he was exposed to altitude. once in
an unpressurised aircraft at 37.000 feet and a month later. in a decompression
chamber at a pressure equivalent to 28.000 feet. On both occasions he experienced
limb pain. visual symptoms and headache. and each time he developed the most
strikingly severe urticarial type of skin eruption (Fig. 7-3) which took 2 days to
resolve.

PERCENTAGE AFFECTED

CLEARED AT ALTITUDE 12%

CLEARED AND RECURRED 5%

EASED PARTIALLY 3%

UNABATED 80%

ONSET   ARBITRARY TIME SCALE   DESCENT

THE INTENSITY OF TONE INDICATES SEVERITY OF SYMPTOMS

Fig. 7-1   Symptom outcome.

DISAPPEARANCE OF BENDS ON DESCENT

☐ DESCENT STARTED FROM 37,000-38,000 ft.

■ DESCENT STARTED FROM 30,000-32,000 ft.

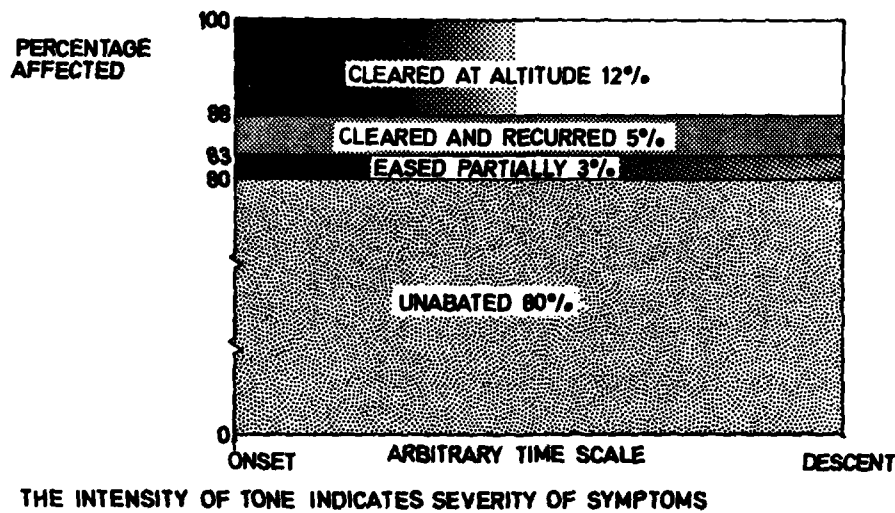PERCENTAGE OF BENDS RELIEVED

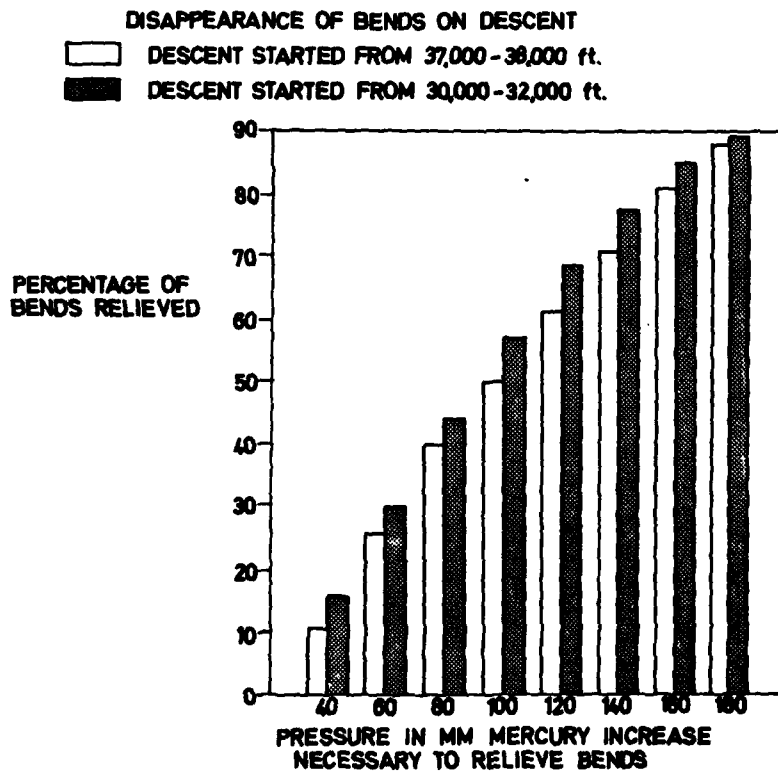PRESSURE IN MM MERCURY INCREASE
NECESSARY TO RELIEVE BENDS

Fig. 7-2 The effectiveness of various ambient pressure increments in
the relief of bends (Motley, Chinn and Odell, 1945).
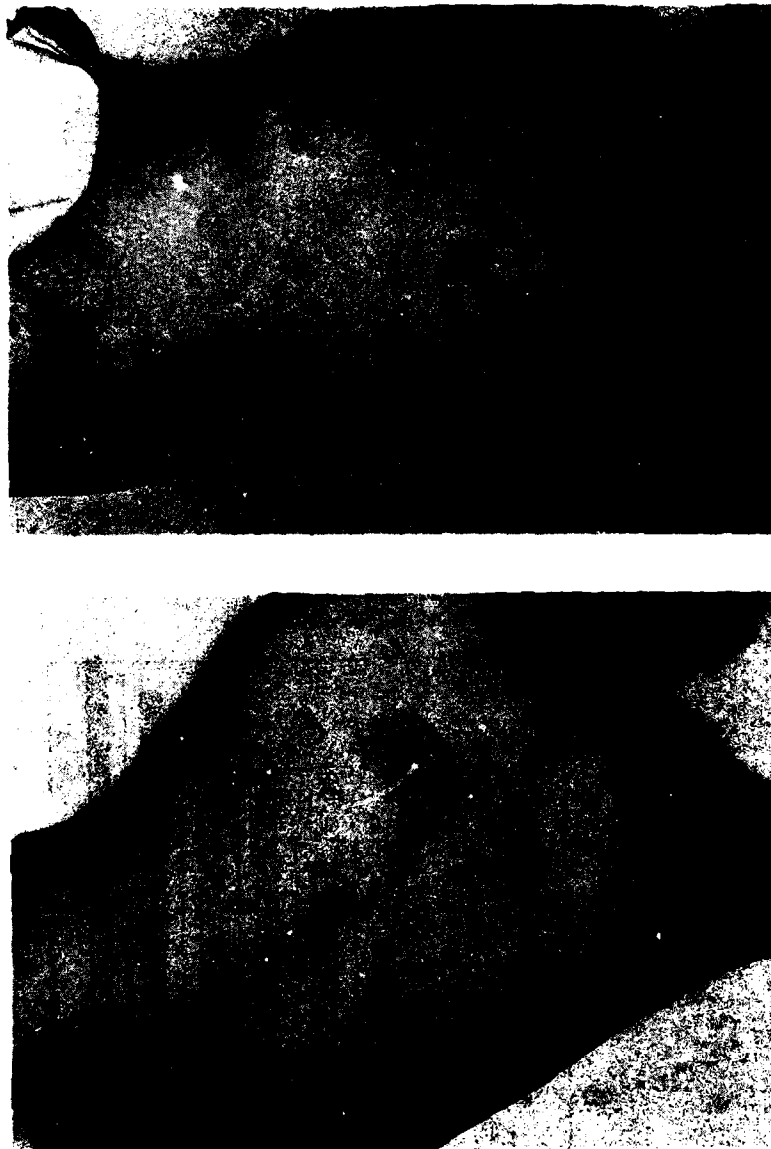Reproduced by permission of the Aerospace Medical Association

Fig. 7-3 Giant urticaria provoked by high altitude flight (Case 14).

Visual Symptoms

Blurring of vision and scotomata generally respond rapidly to descent, disappearing within a few minutes. When associated with headache they more commonly persist.

Motor and Sensory Disturbances

These manifestations of C. N. S. dysfunction are less dramatically responsive to descent than some symptoms, particularly if combined. Thus weakness of a limb or limbs almost invariably resolves within a few minutes, but if paraesthesia, numbness or heaviness are also present, the sensory disturbances may outlast the motor disorder.

Very rarely the neurological disturbances persist, as in the case of von Döbeln and Höök (1954).

Headache

Headache, which is commonly unilateral and associated with visual disorder in a migraine-like syndrome, often lasts for some hours after descent. This is particularly true in persons with a personal or family history of migraine. In such cases nausea and photophobia are occasionally present.

Collapse

The recovery from circulatory collapse upon descent is generally quite remarkable. If the symptoms and signs are caught early, the sufferer experiences in most instances an almost immediate improvement as descent is carried out. Where consciousness has been lost, it is almost invariably regained within one or two minutes, provided that the victim is placed in a horizontal position.

In thirty-two cases seen personally, of whom two actually became completely unconscious in the decompression chamber, only eight did not feel completely or almost completely recovered within a few minutes of descent. In such an event the usual complaint was one of vague nature such as unsteadiness, shakiness or nausea and mild frontal headache.

Post-Descent Syndromes

As has been stated above, the vast majority of persons who develop symptoms experience complete relief upon descent and few have a persistence of discomfort or disability on reaching ground level conditions. An even smaller number have found to exhibit worsening of their condition or the development of a new syndrome subsequently. These cases have variously been described as having 'Collapse', 'Neuro-circulatory collapse', 'Secondary shock', or 'Post decompression shock' (PDS).

The last of these terms has found greatest favour in the United Kingdom. It has the merit that it implies a syndrome developing or arising after an event as opposed to during an event, i. e. it distinguishes the syndrome from 'in-flight' or 'at altitude' collapse. Unfortunately it is a bad term in that the term 'decompression' in subatmospheric parlance refers to the ascent and therefore it strictly can be taken as descriptive of any phase of the flight, real or simulated. This misnomer has arisen, surely, because of the vernacular use of decompression to refer to a simulated exposure, e.g. "he was decompressed yesterday."

The writer proposes here, so far as is known for the first time, to substitute the similar-sounding but much more accurate terms 'Post-Descent Collapse' for those conditions of syncopal or near-syncopal type arising after initiation and generally after completion of descent. When there is evidence of those circulatory changes

which are associated with the condition of shock (i.e. in this context hypovolaemia or persistent vasomotor atony) the term 'Post-Descent Shock' (PDS) will be substituted. It is fortunate that the same abbreviation will serve for this preferable term.

Post-descent phenomena must be subjected to analysis in a systematic fashion if they are to be understood or their nature is to be investigated in a clear-cut manner. It is proposed, therefore, to consider this topic under the following headings:-

Antecedent symptoms

Mode of onset

Characteristics and classification of syndromes

The incidence

The outcome; recovery, partial recovery or death

The clinicopathological and pathological findings

Diagnostic problems

Before developing this analysis, however, it must be explained that it is unavoidable that some overlap will occur. In particular it is necessary to refer to various types of syndrome when discussing antecedent conditions. It is therefore worthwhile pointing out that the main classes of condition are migraine-like, circulatory, neurological and neuro-circulatory, to which must be added a miscellaneous, often bizarre, group.

Antecedent Symptoms

Pezzi (1937) was the first to comment on post-descent migraine; in his case it followed bends. Grulee (1942) appears to have been the first author to refer to a need to admit cases of altitude decompression sickness to hospital; his eleven cases were one bends alone, nine bends and chokes and one chokes. Goggio (1943) described 122 cases sent to hospital, analysing the primary symptoms in detail, as did Masland (1943) with his fifty-five cases. There followed a spate of reports, from Engel et al (1944), Brown et al (1945) and Goggio and Houck (1945). Adler, in 1950, published what must remain the authoritative review, listing 314 cases (which included many of those reported earlier by other authors).

Since then the literature has largely comprised reports of single cases or small series. Examples include Halbouty and Long (1953), Cotes (1953), Halbouty and Heisler (1955), Schneck (1957), Majumdar (1957), Berry (1957, 1960 and 1962), Rudolph et al (1961), Berry and Smith (1962), Coburn et al (1962), Fryer (1964), Flynn and Womack (1963) and Cannon and Gould (1964). A striking case was published anonymously in a US Navy Flight Safety Magazine in 1962. In addition, there have been a number of reports on fatal cases, (reviewed separately in a later chapter) and a collection of past cases from the literature by Malette, Fitzgerald and Cockett (1961).

Authors' classifications are never truly comparable and it rarely proves possible to combine data from several sources in any satisfactory fashion. However, it is possible to assemble three large groups from the literature. Firstly 143 miscellaneous cases are analysed in Table 7-1.

It is to be noted that of the twenty-one uncomplicated bends cases, nineteen were succeeded by a migraine-like syndrome without manifestations of shock. Of the three cases with no symptoms reported at altitude, one (reported by Brown et al,

Table 7-1   Analysis of symptoms at altitude in cases of subsequent severe
            non-fatal post-descent syndromes   (miscellaneous sources)

Symptoms at Altitude	Number	Proportion (%)
Bends	21	14.7
Bends + neurological	12	8.4
Bends + chokes	29	20.3
Bends + chokes + skin	15	10.5
Bends + collapse	32	22.4
Bends + abdominal pain + collapse	1	0.7
Chokes (usually + collapse)	13	9.1
Neurological	5	3.5
Neurological + headache	2	1.4
Neurological + skin	1	0.7
Primary collapse	7	4.9
Abdominal pain + collapse	1	0.7
Hypoxia, followed by collapse	1	0.7
None	3	2.1
Total	143	100%

Table 7-2   Analysis of primary symptoms at altitude in cases of subsequent post-
            descent syndromes (Adler's Data, 1950).

Main Symptoms at altitude	Number	Proportion (%)
Bends (almost always + collapse)	146	46.5
Bends + chokes	53	16.9
Chokes	46	14.6
Abdominal pain	15	4.8
Bends + abdominal pain	9	2.9
Bends + chokes + abdominal pain	6	1.9
Chokes + abdominal pain	4	1.3
Primary collapse	35	11.1
	314	100%

1945) was similarly of migraine only and another, reported by the same authors, was of amnesia, possibly hysterical.

Alder's analysis is marred by his break-down of symptoms, from which it is hard to distinguish between primary and post-descent manifestations. However, from his table 6, it is apparent that his main categories were as shown in Table 7-2.

Berry (1958) reported on 125 cases of 'grade IV' reactors i.e. those requiring hospital treatment, among those tested or subjected to training runs in decompression chambers in 1950-1955. His totals do not tally absolutely from one table to another, but it would seem that the closest one can achieve to a comparison with Tables 7-1 and 7-2 is that shown in Table 7-3.

Compared with these series (Tables 7-1, 7-2 and 7-3) the writer's personal cases make a rather unimpressive total. However, among the 140 or so cases of severe decompression sickness seen and the over 150 additional sets of documents studied in detail, there are a reasonable number of post-descent phenomena. To these cases can be applied analytical criteria at least as good as, if not better than, those used by other reviewers, for it must be remembered that Masland, Adler, Berry, Goggio and others have all reviewed data which were largely if not entirely gleaned from reports sent in from airfields, test centres and hospitals other than those at which they worked.

The results are shown in Table 7-4. They do not differ markedly from the data of the previous tables except perhaps for the numbers of cases originating with severe skin irritation and the low incidence of chokes.

If one ignores Berry's figures (for whose cases insufficient information was published) and attempts to find a compatible classification for the other series, Table 7-5 results.

From examination of Tables 7-1 to 7-5 it would seem clear that the symptoms preceding post-descent syndromes are proportionally distributed in much the same fashion as are those unassociated with any such sequelae (vide Chapter 3). The major distinguishing feature is the remarkable rarity of bends unaccompanied by impending or actual secondary collapse, or other complications. It is unfortunate that the largest series (Adler's)does not give data on this point, but it is clear from tables and the writer's experience that straightforward bends is extremely rarely followed by the post-descent manifestations of decompression sickness. When such complications do arise they are generally migrainous in character.

Even more striking is the near-total absence of cases without antecedent histories of primary symptoms at altitude. Of the four which have been found in the literature or encountered in practice one was quite clearly largely if not entirely psychogenic in origin (see Chapter 10 for this case), one was of strange character, predominantly amnesic, a third developed straight-forward migrainous symptoms and the fourth merited no more than a passing reference. As has been stressed elsewhere, symptom recognition is almost entirely subjective and in conditions of tests the temptation to conceal symptoms is large. It may well be that the asymptomatic case is in fact spurious. Adler was justified in assuming, as did Masland (1943), that "If an individual has no symptoms during a low pressure chamber flight, there need be little fear of a late reaction". In fact this statement is clearly valid.

Little has been commented in the literature on the extreme rarity of symptoms after straightforward bends. Perhaps this is because of a tendency during the war years,

Table 7-3 Analysis of symptoms at altitude in cases of subsequent severe
post-descent syndromes (Berry's data, 1958)

Symptoms at altitude	Number	Proportion (%)
Bends, abdominal pain, chokes etc. almost always complicated by signs of collapse	73	58.4
Primary collapse	5	4.0
Neurological (including visual)	47	37.6
	125	100%

Table 7-4 Analysis of symptoms at altitude in cases of subsequent non-fatal
severe post-descent syndromes (seen by or referred to the author)

Main symptoms in chronological sequence	Number
Bends	4*
Bends + neurological (mostly visual)	9
Bends + chokes	4
Bends + collapse	17
Bends + abdominal pain + collapse	3
Bends + abdominal pain + chokes	1
Bends + neurological chokes	1
Chokes	2
Neurological	5
Neurological + bends + chokes + collapse	1
Primary collapse	3
Formication	1
Formication + bends	2
Formication + chokes	3
Formication + bends + chokes	1
Formication + neurological	1
None (followed by bizzare symptoms)	1
	59

*   Three of these 4 developed migraine-like symptoms only. The fourth had
endeavoured to endure bends at altitude for 97 minutes.

Table 7-5 Antecedent symptoms of post-descent syndrome cases. (Compilation
of data from Tables 7-1, 7-2 and 7-4).

Symptoms	Number	Proportion (%)
Bends or bends plus other symptoms*	262	50.8
Bends and chokes	101	19.6
Chokes or chokes and other symptoms	65	12.6
Primary collapse	45	8.7
Neurological, simple and complicated	14	2.7
Abdominal pain followed by collapse	16	3.1
Miscellaneous (including those starting with skin symptoms)	9	1.7
No symptoms at altitude+	4	0.8
	516	100%

* Of those twenty-five specifically known to have been bends only, twenty-two are
known to have been followed by migraine-like syndrome only.

+ These four include one migraine only and two atypical post-descent reactions
of probable functional origin.

when motivation to pass the candidates was high, when supervision was often
marred by inexperience, fatigue and overloading, to allow cases of bends to pro-
gress to the stage of impending or actual collapse, or to the development of chokes,
visual disturbances etc. before making a decision to carry out a forced descent.
However, it has been striking in subsequent series, particularly the 28,000 foot
RAF test, that those not exhibiting signs or symptoms other than limb pain do not
subsequently develop post-descent complications.

The incidence of antecedent chokes is high in comparison with the overall figures,
referred to in Chapter 3, for symptoms at altitude. This is true of both US and
British series. The same applies to primary collapse. The tendency in US
reports has been to consider the altitude and the post-descent symptoms as a
whole and to classify them accordingly. Thus collapse cases may include not only
what the writer would term primary and secondary collapse but even cases of such
symptoms as visual disturbance or skin irritation which proceeded to post-descent
deterioration.

The Onset of Deterioration

As has already been pointed out, the vast majority of persons suffering symptoms
at altitude experience complete and lasting relief on descent. The remainder
exhibit a range of reactions from, at one extreme, a relentless, rapid downhill
progression to death, to an absolutely lucid interval followed by no more than brief
transient malaise.

Adler (1950) unfortunately categorised altitude and post-descent manifestations
together, but a measure of the range of signs and symptoms encountered is his
compilation of over ninety clinically observed abnormalities.

Classification of Post-Descent Symptoms and Signs

In 1950 Adler wrote that "no classification either on the basis of time of collapse,
mechanism or symptomatology can be completely satisfactory because the neur-
ological and circulatory symptoms are varied and very few cases are clearly one
or the other". This statement is still valid.

Masland (1943) had tried to separate cases on the basis of four classes:

a)   Primary shock - symptoms at altitude with recovery on descent, although
       some showed bradycardia for as long as twenty-four hours and a few others
       developed secondary shock;

b)   Secondary shock - collapse arising as a delayed phenomenon after other
       symptoms, either whilst still at altitude or after descent;

c)   Primary nervous system involvement - commonly associated with chokes,
       clearly involving the CNS, often associated with primary or secondary shock;

d)   Disturbances of cardiac origin - often associated with other symptoms, only
       distinguishable by the detection of a cardiac disorder.

This classification lends itself to the segregation of a few examples, but the ma-
jority of cases even including some cited by Masland, do not fall clearly into any
one of the four groups. The impression gained is that of a complex continuum of
cases from which examples may differ widely or resemble each other closely
according to their selection, but which defies any attempt to categorise into distinct
groups.

Adler (1950) attempted to sort out his 314 collected histories on a basis of
Neurological, Circulatory and Neurocirculatory types.   These occurred in pro-
portions of 24: 23: 267.   This seems to be a much clearer classification, but one
is still faced with problems.   For example, if a person develops visual symptoms
and then paresis of a limb, accompanied by pallor, sweating and peripheral vaso-
constriction, is he exhibiting a neurological disorder and a vasomotor response to
the awareness of his condition?   Or, is he simultaneously showing neurological
and vascular reactions to altitude?   Similarly, if two persons experience a typical
vasomotor collapse with pallor, sweating, dizziness and loss of consciousness but on
recovery one has an epileptic fit and the other does not, is the former different in
any way from the latter other than perhaps having a more sensitive motor cortex,
a more precarious local cerebral circulation or more profound hypotension?

Taxonomic exercises of this sort are fascinating but are they fruitful?   It is sug-
gested that the value of a classification lies in its success or otherwise in separating
classes which have differences of aetiology, prognosis or therapy.   If almost or
totally arbitrary sections of a continuum are selected but no differences can be
found in their subsequent progress, their response to treatment, or their internal
disturbances as revealed by clinical or pathological investigation, the exercise
would appear to be sterile.   What is more important, it may have diverted attention
from more promising modes of comparison.

The writer remains unconvinced of the usefulness of classifications based on the
analysis of Masland or Adler, but has difficulty in proposing an alternative.
The most important aspects of post-descent phenomena are their seriousness in
terms of risk of irreversible change and their response to therapy.   Can any ana-
lysis separate those cases of good and bad prognosis and good and bad response
to therapy on a basis of any signs or symptoms?   If so, the clinical care of cases
is simplified enormously, since if the overall prognosis is good even in the absence
of treatment, the avoidance of unnecessary and perhaps inherently slightly hazar-
dous therapy in the majority of cases could result, with benefit to patient and practi-
tioner alike.

On this basis, there would only appear to be two clear-cut features:

(a)   Migraine arising during or after exposure to altitude has a uniformly good
       prognosis except when it is accompanied by or complicated by signs of general
       circulatory or motor dysfunction.
(b)   Loss of consciousness with delayed, incomplete or failure of recovery on
       descent bears a bad prognosis.

Quite distinct from classification of an academic type, there arises a need on
occasion, to find a convenient method of listing the characteristics of post-descent
signs and symptoms in order to construct a picture of the syndrome or syndromes
which arise, single or in combination.   On these grounds alone the following groups
are discussed:

1.   Migraine-like
2.   Skin Changes
3.   Visual
4.   Focal CNS
5.   Cerebral Higher Centres
6.   Abdominal Pain
7.   Circulatory 'shock'
8.   Miscellaneous

Migraine-like

The definitive study on this subject is by Engel et al (1944) and the general obser-
vations of several authors have been gathered by Ferris and Engel (1951). In
some cases visual symptoms such as scotomata, blurring and fortification spectra,
develop at altitude together with a typical unilateral headache (see Chapter 3) and
the condition runs it characteristic course over several hours after descent. In
the worst cases an homonymous hemianopia may develop and the headache may be
associated with vomiting. The neurological picture, including the EEG, is charac-
teristic of migraine (Fig. 7-4).

Although the US authors were able to collect a number of cases of this type, they
are, in the writer's experience, extremely uncommon. From the literature it
would seem that their prognosis is extremely good. It must be stressed that this
applies to those cases without other symptoms. When complicated by signs of
severe vasomotor collapse, skin changes, chokes or bends pain at altitude or when
accompanied by signs other than those of simple migraine, the prognosis
appears to be governed by that of the complications.

Occasionally, as mentioned in the discussion on antecedent symptoms, bends at
altitude is followed by migraine on descent. In such cases it is common to find
a past history of migraine although it must be emphasised that only a minority of
migraine sufferers find that their symptoms are triggered by decompression.
It is also true that many cases seen after decompression give a minimal or negative
history of migraine under other circumstances. A good example is that of:

Case 15

> An officer, navigator, was seen on 12th August, 1952. He was aged 29, fully
> fit and of average build. He was decompressed to 37,000 feet and held at that
> altitude. In spite of a warning he insisted on playing a card game with his collea-
> gues. After 14 minutes he developed bends pain in the right forearm and hand,
> and in the left elbow and hand. After 6 minutes it was clear that he was in consid-
> erable discomfort and although he was willing to continue the run he was transferred
> to the lock compartment and removed from the chamber. He felt completely fit
> but as a precaution he was told to remain in the vicinity of the decompression
> chamber. An hour later he commented that vision in the right half of the visual
> field of both eyes was blurred, progressing to a complete homonymous hemianopia.
> He developed a severe right-sided headache and became pale. His pulse and
> blood pressure were normal.

> Over the next 4 hours symptoms resolved completely. On questioning he denied
> any history of migraine, either personal or familial. However, on being asked
> "have you ever experienced anything like this before?" he stated that he had, a
> few months earlier, had a similar visual field defect, headache of crippling seve-
> rity, nausea and vomiting, lasting for 18 hours! His doctor had been unable to
> reach a diagnosis, the term migraine had not been mentioned!

Those who react in this fashion to altitude seem prone to do so repeatedly. The
writer has seen three such cases personally. For example:

> The same navigator did not reveal to his superiors that he had experienced such
> symptoms following the decompression test and his medical officer failed to take
> any action on receiving the report of his severe migrainous response. He con-
> tinued in his flying work, concerned with research on radar and communications
> equipment. In January 1955, 29 months after the test he was flying in a research
> aircraft which was capable of protracted flight at high altitude without the benefits
> of pressurisation. After an unspecified period he developed a severe headache,
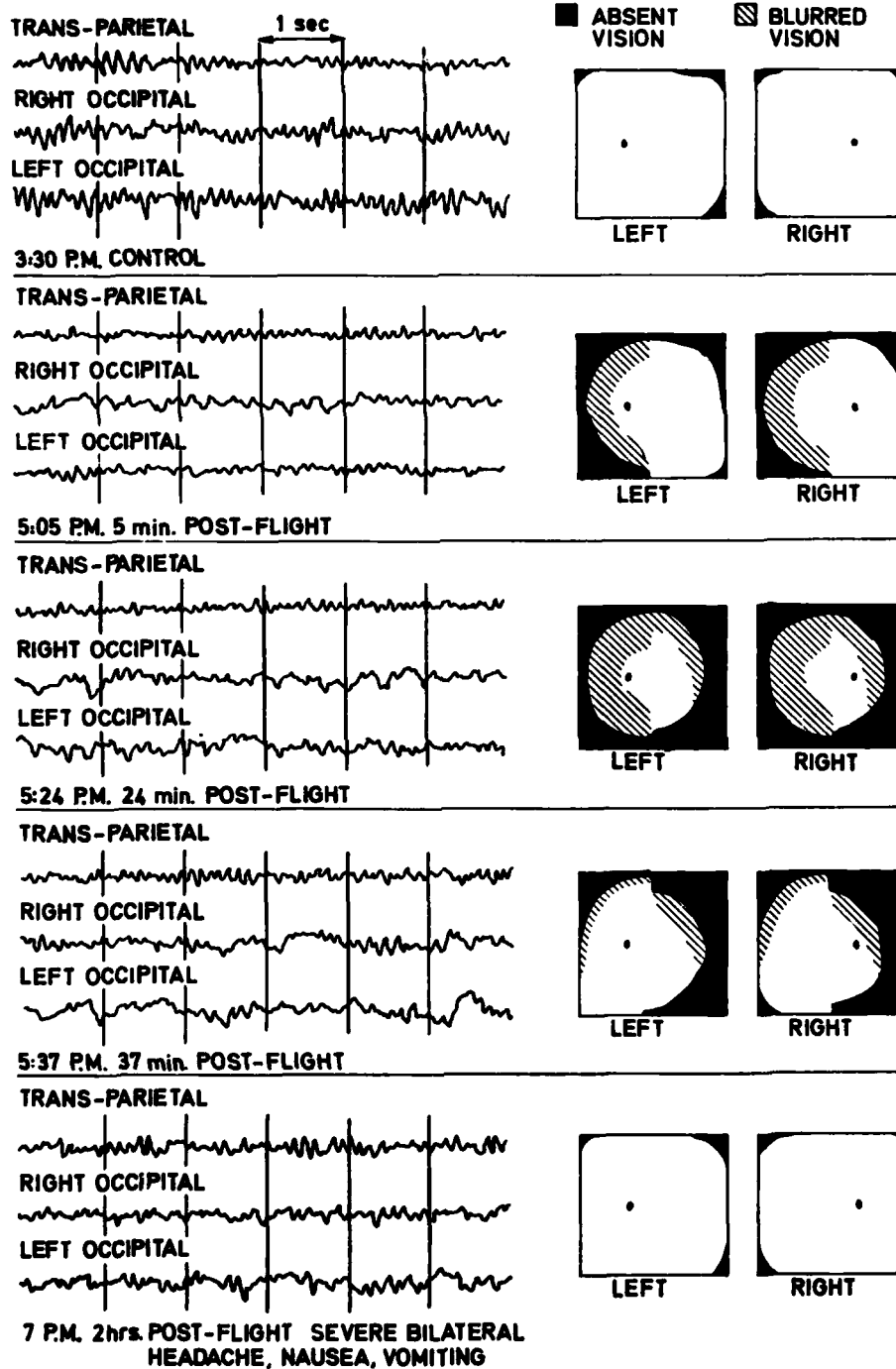> became pale and vomited. He recovered during the descent but one hour after

Fig. 7-4   The EEG and perimetry data from a migraine-type post-flight reaction (Ferris and Engel, 1951).

landing he developed a unilateral headache so severe that the medical officer felt
it necessary to treat him with a ¼ grain of Morphine.   The patient was referred to
the neuropsychiatric consultant who recommended a reduced employment category
with an imposed limitation of 25,000 feet.   Tragically he was killed a few weeks
later in an aircraft accident.

Skin Changes

The skin changes described in Chapters 3 and 4 often, as was mentioned, persist
for a period of up to two days.   Very often exquisite tenderness develops in the
reddened areas.   Only once has persistent formication been seen.   This affected
the sacral region and was associated with tenderness, blotchy redness and quite
marked local oedema.

In the very severe cases of circulatory collapse, particularly those associated
with chokes, mottled cyanosis of the trunk and shoulders may become very intense
and on many occasions the lesions have been referred to as petechial.   As mentioned
in Chapter 4, those cases in which pressure with a glass surface has been attempted
always show blanching, demonstrating that the blood is still within vessels.

Visual Disturbances

Apart from the migraine-like picture referred to above, there are two cases in the
literature of transient blindness.   Grulee's (1942) Case 5, for example, after
experiencing hypoxia was taken to 38,000 feet.   He developed mild bends in the
shoulders, became unresponsive and unco-ordinated.   A descent was carried out
over seven minutes and the victim was found to be confused and irrational.   Some
five to ten minutes later he became lucid but complained of total blindness, which
fortunately resolved completely in the next fifteen to thirty minutes.   No fundal
changes could be detected.

Masland's (1943) Case 2C had a poorly documented exposure to 38,000 feet and
apparently was unconscious for twenty minutes.   He had extremely severe shock
with haemoconcentration etc. and was blind for a day, gradually recovering sight
over the following four days.   His retinal fields showed marked arterial and
venular narrowing.

Focal Central Nervous System

Very rarely a discrete neurological disorder becomes apparent after descent.   On
occasion this is in association with migrainous symptoms.   For example a case,
cited by Masland (1943 and 1946), developed bends in a knee and both shoulders,
after almost two hours at 33,000 feet.   The pain eased on descent but he developed
blurring of vision, numbness of the left hand and aphasia.   These symptoms lasted
some quarter of an hour to disappear quite rapidly, but were followed, in turn,
by severe right hemicrania and nausea lasting twelve hours.   He had a history of
migraine.   The syndrome fits almost exactly the description of severe migraine
given by Walshe (1947).

Isolated disorders of spinal cord or cortical origin are extremely rare, although
fleeting changes in power and reflexes are not uncommon in cases with extreme
circulatory shock.   The most renowned and severe case is that already referred
to reported by Höök (1958), of a test pilot aged 36, decompressed to 39,000 feet.
His primary symptom at altitude was abdominal pain, followed by numbness of
arms and legs.   In spite of prompt descent he developed what would seem to have
been a condition indistinguishable from that following interruption of the anterior
spinal artery at a cord level of the seventh cervical segment.

Purely sensory disturbances, other than those of vision, appear not to have been reported. Numbness, heaviness and tingling are frequently mentioned, but always in association with motor weakness, shock or migraine.

Cerebral Higher Centre Disturbances

In association with varying degrees of malaise, shock, headache or other symptoms there have occurred a few cases of complex central nervous disorder of great interest.

Loss of volitional control in the absence of true motor disorder is an example, seen by the writer.

Case 16

> A 25 year old cadet, with no history of any neurological disorder was subjected to decompression to 28,000 feet. He was quite fit at the time apart from the slight residua of a 'heavy night' at a party on the preceding evening. After 30 minutes at altitude he felt that his right hand was numb and he felt flushed. His peripheral vision became wavy and his central vision blurred, whilst he began to feel hot, nauseated and weak in both arms. He was transferred to the lock compartment and a rapid descent was carried out. During the descent he experienced what was reported as paralysis of both arms; fortunately this was brief and he made a full recovery over 30 minutes.
>
> At interview a few days later it became clear that the paralysis was no simple diplegia. When asked about the disorder he stated that he could move neither arm. However, when asked how he was sitting at the time he said that he was holding both arms out-stretched at shoulder level. What was wrong was that, although ne could achieve this position, he could not order his arms to do anything else. Even when movement began to return, he could not readily move the correct arm when asked to move the left or right.

This case has a remarkable parallel in an account of an in-flight occurrence, published anonymously by the US Navy Aviation Safety Center (1962). Following a rapid decompression from 8,000 to 35,000 feet a navigating officer developed bends. He felt as though his arms were floating in mid-air and had little control over them. Later he became unable to move either arms or legs (vide Case 6, Chapter 3) and could not let go of his pencil. When he tried hard to move his hand he saw it was moving but he had no sensation of motion or perception of the position of his hand.

Another complex case was reported to the Institute of Aviation Medicine by an aircraft manufacturer. During the course of a test flight in a large prototype airliner at 25,000 feet an experienced flight test observer complained of feeling very hot and ill. He almost immediately lost consciousness and he remained thus for some fifteen minutes in spite of being laid flat and receiving an augmented oxygen supply. He was in coma or semicoma for eight days, during which time he developed a spastic quadriplegia which later resolved to involve mainly the left arm. although his legs remained slightly spastic and his plantar responses were persistently extensor. Two months later his left arm was clumsy, his gait stiff and, most interestingly, he appeared to have a disturbance of body image in that his right leg no longer felt part of his body.

A much more striking case of higher cerebral dysfunction was recorded at Farnborough in 1941 (Roxburgh, 1953).

Case 17

A pilot, aged 34, was decompressed, without supplementary oxygen, to 28,000
feet in order that he might experience the signs and symptoms of hypoxia. He
reacted in a normal fashion, showing deterioration of writing ability culminating
in clonic spasms of the hands. His oxygen supply was turned on and the climb
maintained. He complained of tingling in both arms to which was added pain in
hands, shoulders and knees as he passed 32,000 feet, some 3 minutes after oxygen
was first given. Just over a minute later he became very pale; sweating, which
had been present for some 5 minutes, increased and he collapsed, losing conscious-
ness. Descent was immediately initiated and he recovered consciousness passing
25,000 feet, but complained of inability to move his right arm, which tingled. His
pulse was, at this time, 70/min. and regular, his tendon reflexes were normal in
the right arm, to which power progressively returned. At ground level (at about
2.45 p.m.) his blood pressure was found to be 102/74. He appeared quite well
except for slight sweating and,as he was feeling fully recovered, he was allowed to
watch an instructional film. (He later revealed that the tingling in his right arm
had taken some 5 minutes to clear after descent was completed).

At some stage, about which he later seemed uncertain, but approximately an hour
after descent, his visual acuity deteriorated and he felt very weak and sick. He
developed a severe frontal headache and vomited several times. He found difficulty
in controlling fine movements of his right hand, picking up an ashtray instead of an
adjacent cup, spilling tea when pouring it owing to tremor and he lay down on his
bed. He felt very thirsty. When he went to fill a glass at the wash basin he had
great difficulty, because, confusing laterality, he kept putting the glass under the
wrong tap. He became confused and his memory for the events of that night are
extremely vague. He was seen twice by a doctor, who found him restless but
drowsy, not disoriented in place or time, but with marked ataxia of both arms.
When he rose next morning he could not open the door of his room, he had difficulty
seeing the handle and could not grasp it, as he repeatedly moved his hand to the hinge
side of the door. He was taken to hospital, confused, drowsy, clumsy, with poor
orientation but cheerful. His visual acuity was poor and he was found to have mono-
cular diplopia. He had difficulty controlling voluntary movement of his arms and
had a strange inability to make eye movements on request, although random move-
ments were full.
Whilst being examined he suddenly had a classical epileptic grand mal seizure.
During the next few days he had bizarre neurological disorders, varying in character
and intensity. He had strange visual disturbance, some words on a page of writing,
for example, appearing inverted: he made strange errors in trying to read a watch-
face; he had complex and vivid visual hallucinations in the darkness on the third
night, dismissed immediately by switching on the light. An EEG two days after the
incident showed a focus of low voltage, low frequency (2 c.p.s.) waves in the lower
part of the right parietal region. This abnormal rhythm decreased in amplitude to
revert to a normal pattern after some 10 days, when he was discharged to take sick
leave and thence to return to duty.

A remarkably similar case was seen by the writer in 1957. In the light of exper-
ience accumulated in the intervening sixteen years, a fuller history was obtained.
A summarised version is as follows:-

Case 18

A 33 year old pilot who had amassed a very considerable amount of flying experience
at altitudes of up to 20,000 feet and who had twice been subjected without untoward
result to demonstrations of hypoxia in the decompression chamber, was posted to a
unit to undergo conversion training for jet aircraft flying. He was in good health
and not subjected to any emotional stress. He was somewhat overweight.

On September 23rd at 10.30 a. m. he was subjected to a decompression demonstration. He was taken to 25,000 feet without oxygen, at 3,000 to 4,000 ft/min. There he remained, writing and performing simple tasks until mental impairment became obvious. At no time was he unconscious or jactitating. His oxygen regulator, set to 'high' flow, was turned on from outside the chamber and he made a rapid recovery.

The Medical Officer in charge of the chamber then discussed the symptoms and signs of anoxia from his station outside the chamber and after 2-3 minutes, being satisfied that the subjects were fully recovered, he ordered an ascent at 2,000-3,000 ft/min. to 37,000 ft. During the ascent or at the new altitude, the subject complained of moderate abdominal distension. At 37,000 feet he was told to turn off his oxygen and to commence writing again. After a short period (2 minutes in the estimation of the Medical Officer, 30 seconds in the estimation of the chamber operator) he stopped writing and looked dazed and cyanosed. He developed blurring of central vision, pain in both knees and a sharp tight feeling in his groin and his back. He was told to turn on his oxygen supply, but although he looked up towards the Medical Officer, he did not carry out this instruction. His right hand began to twitch and he appeared to be very dazed. His neighbour was told to turn on his oxygen. This done, the twitching increased for a while, but very soon he recovered and carried on writing as though nothing had happened. When asked what he remembered of the stay at 37,000 feet, he said that he could recollect being told to turn on his oxygen and failing to respond. The next man's oxygen was next turned off, but very soon after this the subject was observed to be hyperventilating and although he obviously heard a request to breathe slowly, he did not respond and rapidly became 'inaccessible'.

A rapid descent was made (at 12,000-15,000 ft/min.) and at about 11,000 feet this was stopped as he had apparently recovered, was alert and was breathing more slowly. After 3 or 4 minutes descent was recommenced at 12,000 ft/min. to 5,000 feet and more slowly to ground level. At some stage in this descent he shook his hands and flexed his wrists repeatedly as though they were painful. He then disconnected his own oxygen supply and left the chamber with other 2 subjects.

The very experienced chamber operator was of the impression that this man was ashen in colour after the first anoxia demonstration at 25,000 feet and never picked up fully thereafter. He sat in a crouching attitude and "went out" unusually rapidly on being deprived of oxygen at 37,000 feet. Again he recovered poorly and was of ashen appearance. He was "not with us" until descent had been made to about 13,000 feet. On leaving the chamber and being asked how he felt, he said that he was a little "light-headed" and had a frontal headache. He was asked whether he had any aches or pains and replied that he had none, although he later stated that he had at that time nausea, frontal headache, pain in the groins and felt weak at the knees. He left, in the company of a colleague and proceeded to the nearby Officers Mess. He ate his lunch but his colleagues observed that he was pale and was perspiring. Half an hour later he drew from stores some volumes of Air Publications and signed for them quite distinctly and without difficulty. He reported at the flight offices and was noticed to be pale and he complained of feeling tired. He was no longer sweating. As there were no further duties to perform, he went back to the mess, ate his tea at about 4 p.m. and retired to bed, where he had severe nausea, frontal headache, pain behind the knees and blurred central vision still. To a colleague he appeared normal. He noticed once, on waking, that the bed was in great disorder and he took $1\frac{1}{2}$ hours to re-make it, because of difficulty with vision and co-ordination. He could not appreciate the shape of the bed and was unable to decide which was the longer dimension of the sheets. He had difficulty taking his pyjamas from the drawer. He dare not look down because this made his headache much worse. He felt "as though I had been on a round-about" although he had no vertigo. In trying to get a drink of water he broke the glass and couldn't turn on the tap, either because he could not see it except in his peripheral field or because

of a defect in co-ordination. He slept intermittently and noticed that his headache was worsened by coughing. He had no abnormality of bowel function and passed very little urine. He felt cold.

On Tuesday morning, 24th September, his neighbour called on him. He noticed that the bed was very untidy. Otherwise there was no disorder: he had hung up his own uniform and had left his other clothes quite neatly arranged. For the first time since going to bed he complained of a headache. The Medical Officer was sent for and saw him in his room at 11 a.m. He elicited a history of frontal headache and nausea, anorexia and a pain in the lumbar region. He did not have a sore throat. On examination he appeared hot and was sweating slightly. His temperature was 99.2°F. In view of the prevalence of influenza on the station (72 cases seen that day), the Medical Officer tended to concur with the patient's own diagnosis of flu and he gave him some codeine compound tablets, told him to stay in bed and arranged to visit him again later that day. Having been absent from the unit on the previous day, the doctor did not know that this man had been in the decompression chamber on the previous day.

At 5 p.m. a colleague visited him and found him considerably worse. He said that his headache was much worse in spite of the tablets (4 had been consumed). He got out of bed to get a cigarette and was obviously very unsteady and appeared to be giddy. He failed to find his cigarettes in his tunic and got back into bed. He said that he "couldn't see well". On being handed a packet of cigarettes he dropped them in the bed and was unable to retrieve them. On being given a single cigarette it was apparent that his hand was very shaky and he said that everything was "dim and misty" and that he couldn't see anything directly in front of him. He was pale, not cyanosed and not sweating. At 7 p.m. the Mess porter went to his room and witnessed a generalised fit. He sent for the Medical Officer who arrived at 7.15 and found the patient confused, restless and disorientated in time and place. Whilst being examined he had a typical grand mal epileptic seizure. He was immediately taken to sick quarters. There he had another epileptic fit. On this occasion he micturated, passing a very small quantity of urine. His plantar responses were extensor just after the fit. He was sweating a little and felt clammy. He was transferred to an RAF Hospital by ambulance, a distance of 30 miles. By this time the probable relationship between the decompression and the symptoms was first recognised. On arrival at the hospital he was found to be comatose and confused. Whilst being examined by the duty Medical Officer he had another grand mal fit. This was typically Jacksonian. First his face became quite expressionless and he stared directly ahead. His eyes began to turn upwards and his right hand began to twitch. Soon the whole right arm was moving and then the convulsions became generalised and very severe. He held his breath and became very deeply cyanosed. He lapsed into coma for a while. When seen by the medical specialist at 10.30 p.m. he was however again quite alert but amnesic. He did not know where he was or where he had come from. He was not cyanosed or sweating. He did not present a clinical appearance of shock and his blood pressure was 150/90. His right pupil had been observed to be large and to react sluggishly immediately after his second observed fit, but now was normal again. His left plantar response was flexor, the right equivocal, probably flexor. He passed urine which was noted to be concentrated and free from albumen and sugar. He was given intramuscular phenobarbitone and soon slept. Over the succeeding few days he progressively recovered completely. His EEG, taken on the 4th day, was thought to show "distinct right sided abnormality, suggesting a vascular embolic phenomenon". Three days later it was normal.

The similarity between these latter two cases (17 and 18) is quite remarkable. Both were subjected to hypoxia, both had similar pain; both had a lucid interval,

similar onset of headache and nausea, complex co-ordination and stereognosia defects and finally, grand mal seizures.

Epilepsy is extremely rare as a post-descent phenomena.   Of the total of over 500 cases in the series of Masland, Adler, Grulee and the author, there appear to have been no more than six who had epileptic fits.

Abdominal Pain

Severe abdominal pain by itself or in combination with other symptoms is also very uncommon.   Adler calculated that 4.8% of his cases had abdominal pain alone and another 6.1% had bends, chokes or both bends and chokes also.

The most striking cases have been among those ending fatally.   Whether this implies a causal or a resultant relationship is not known.   Relevant case histories are to be found among the fatal cases.   In general, the pain appears to be of constant or griping type, felt in the centre of the abdomen or less commonly in the epigastrium or just above the pubis.   The pain is almost always associated with very severe nausea and shock.

Circulatory 'shock'

The term 'shock' is likely to stimulate violent controversy whenever it is used and there are those who would even ban its use in favour of such expressions as hypovolaemia.   However, ignoring the question of mechanism, the term has one outstanding merit which, in the writer's opinion, outweighs all other considerations;   to anyone of experience in the fields of medicine or surgery the very word conjures up a clinical picture which is unmistakable.   It is of such emotive value in that, free from any connotation as to aetiology, it gives rise to a clear concept of a syndrome which is common to many conditions, including decompression sickness. In the writer's use of the term in this context, the clinical features are quite simply those seen in such disorders as acute haemorrhage, burns, rupture of a viscus of acute allergy.

The clearest picture is seen in those cases, rare though they may be, where there is a lucid and virtually symptomless interval between the primary symptoms and the onset of shock.   The following description is based on those cases seen by the writer.

The first hint of shock is almost always a vague sense of unease or anxiety.   One man quite clearly stated that he felt jittery.   In its most extreme form this feeling may amount to true angor animi   in which the patient is overwhelmed by a sense of impending doom which is quite out of proportion to the clinical signs.   Simultaneously, or very shortly following, the patient becomes pale and sweating, particularly on the palms of the hands, the brow and in the axillae.   Subjectively he will feel waves of hot and cold sensations and quite characteristically, he will develop a vaguely localised but oppressive frontal headache.   At this stage, although Adler (1950) makes much of the incidence of bradycardia, the impression gained by the writer is that the pulse is very commonly quite normal in rate and rhythm but almost always is small in volume, even thready.   The feeling of anxiety increases and the victim becomes manifestly agitated;   if lying in bed or on a stretcher the characteristic behaviour is rather pointless repeated 'fiddling' with the bedclothes and frequent movement as though trying to alleviate some discomfort.   If seated, it is not uncommon for vertigo or more vague dizziness to occur, particularly on head movement.

Nausea is very common and quite often violent unproductive retching occurs.
The extremities become pale and cold, and intense vasoconstriction is apparent in
the hands. The blood pressure, as measured by auscultation at the elbow, is
almost always normal until the collapse is very advanced. Peripheral cyanosis
is almost always marked and central cyanosis is common.

In the more severe cases, consciousness becomes clouded and not infrequently
behaviour becomes irrational. Occasionally, violent unco-ordinated movements
and noisy phonation are seen. Very commonly when drowsiness is present or
rationality is obscured the patient will react violently to any stimuli such as examin-
ation, venepuncture or even noise. Mottling of the skin across the chest and
shoulders is commonly very marked, amounting to livido. Finally, in the worst
examples coma supervenes.

Recovery can ensue at any stage, although it is extremely uncommon once coma
has developed. Thus the mildest cases may experience no more than transitory
uneasiness, pallor and frontal headache. Others will look very pale and sweaty,
wanting to lie down and then within an hour or so recover often quite abruptly.

Peripheral circulatory changes are often very marked indeed. Even when not
witnessed they may be assumed from the history. For example, in Case 6, ref-
erred to in Chapter 3, in which quadriplegia occurred in flight:

> After landing, this 48 year old officer felt almost normal apart from being very
> tired and rather feeble. He was driven home where, although his room which
> in Aden in March, having had the door and windows closed for several hours,
> must have been very hot, he felt cold and shivered violently, his teeth chattering
> uncontrollably. He went to bed with 4 blankets over him and still felt cold.

In another example:

Case 19

> An aircrew officer was acting as flight engineer in an unpressurised large re-
> search aircraft, flying at 30,000 ft. After 40 minutes he noticed severe pain in
> his right shoulder, which spread to effect his forearm and also the front of his
> chest. After a further 35 minutes his colleagues noticed that he looked very pale
> and was obviously ill. The aircraft was brought down to 25,000 feet, at which
> level the research scientists on board pleaded, successfully, with the pilot to be
> allowed to carry on with their experiment. The engineer, who had felt much re-
> lieved by the reduction of height soon began to feel weak again. He suddenly not-
> iced "a yellow pin-point of light oscillating from left to right and then from the
> left again, seen with both eyes, whether open or closed". This only lasted 2 to 3
> minutes, but he became hazy, clumsy, disinterested in his surroundings to the ex-
> tent of seeming euphoric. His eyesight became very poor.
>
> After 45 minutes at 25,000 feet the descent was resumed and the aircraft returned
> to base. He felt much better but was still a little shaky. He started to drive
> himself home. His recollections of the journey are vague but he well recalled be -
> ing aroused by hooting to find that he had lost consciousness whilst stopped at
> traffic lights and that his fellow road-users did not appreciate his failure to move
> on when the green lights became illuminated.
>
> He managed to reach home without accident, but on arrival he was violently sick.
> He had severe abdominal pain, was breathless; he developed a very severe head-
> ache and to his wife's distress, was cyanosed to such a degree that his facial colour
> was said to match that of his RAF blue shirt.

He was rushed to hospital where he was found to be dyspnoeic, cold, sweaty and
collapsed. No other abnormal findings were recorded and he made a rapid spon-
taneous recovery to be 100% fit by the following day.

These examples give a clear picture of the type of reaction which is apparently
self-resolving. It is only different in degree from the fatal type described in a
later chapter. The main hazard of the milder case is seen in the second of these
examples; the risk of collapse in a dangerous situation. Not only has this occur-
red whilst in control of a motor vehicle; the writer has seen cases who have quite
suddenly become ill whilst in a train, whilst on a railway platform, whilst alone
in a bedroom in the officers' mess and most hazardous of all, in an aircraft (for-
tunately with dual controls).

Miscellaneous

Apart from those post-decompression syndromes listed above, a few cases have
been reported and others seen by the writer which appear to be individually unique
and quite outside the general categories hitherto described. Some may have been
intercurrent illness, quite fortuitously occurring at the time of exposure to altitude.
Others are undoubtedly due to decompression.

Cardiac - Masland (1943) reported three cases of cardiac disorder during or
immediately following decompression. They were of atrial fibrillation, bundle
branch block and coronary artery occlusion.

Cerebro-vascular - Adler's case XIII was of a complex neurological syndrome of
right facial weakness, motor aphasia, deviation of the tongue, sensory loss and
weakness of the left arm. He was diagnosed as having thrombosis of the right
posterior inferior cerebellar artery and his recovery after three months' hospital
treatment was far from complete.

Hysterical - Adler's case XIV (the same as Masland (1943) case 5E) was a bizarre
picture of generalised twitching and staccato speech which was, probably correctly,
thought to be hysterical.

Delayed Neurological - Berry and Smith (1962) described a very strange incident
affecting a 37 year old pilot (their case 3). He developed tingling and mild bends
at about 7 p.m. one evening, in flight at a cabin altitude of 25,000 feet. He was
a little clumsy, but after descent his only symptom was slight soreness of the left
calf. After what was perhaps euphemistically described as 'a social evening' he
rose late next day. In the early afternoon, at least twenty hours after the initial
symptoms, as he was climbing into his aircraft he suffered severe pain in his left
calf which "proceeded up his left leg, into his lower abdomen and down his right
leg". He collapsed, unconscious, for three-quarters to one minute. He made
a complete recovery within a few hours. The only physical abnormality was a
transient extensor plantar response on the right side.

Localised Swelling - Without doubt the most puzzling case is one seen by the writer
in 1956.

Case 20

This experienced 31 year old pilot had a decompression test in December 1955.
After 30 minutes at 27,000 feet he developed a paroxysmal cough which rapidly
became severe. He did not feel faint. A rapid descent was made and the cough-
ing soon passed off. He experienced a generalised headache for some half-hour
afterwards. Otherwise he felt quite fit. At no time did he notice an inspiratory

catch such as is typical of chokes but he produced a little viscid sputum. The
general opinion was that the cough should be attributed to a mild cold which he had
at that time. A few hours later he noticed swelling of the right forearm, most
marked on the ulnar side. This was not painful or irritating. It subsided in
about 2 days and left no trace; in particular there was never any sign of bruising.

On the day prior to examination (14.2.56) this officer was again decompressed.
After one hour at 27,000 feet he noticed dryness of his throat and he started to
cough. Again he noticed no inspiratory limitation, but felt breathless and found
his cough worsened by movement to the lock. Although he made no mention of it
at the time, he admits that he had felt a mild ache in his right elbow and in the
right inguinal region, for some 5 minutes. About 10 minutes after the descent
the cough resolved. The respiratory symptoms were, he stated, like those one
would expect on leaving the squash court and walking out into very cold air. On
examination his blood pressure (right arm) was 110/65 and his pulse 88. Very
soon after leaving the chamber it was noticed that the right arm was mottled and
beginning to swell. Some 2 hours later the swelling subsided, only to reappear
after an hour or two. It was then noticed that the right lower abdomen appeared
swollen, felt heavy and wobbled. The skin was noted to be reddened in large ill-
defined patches. There was in the arm and abdomen a dull ache. On the morning
of 15th February, the swelling was still present and the right side of the face app-
eared puffy. No symptoms were noticed in the mouth, ear, nose or throat. No
eye disturbances were noted. On examination it was clear that there was, indeed,
swelling of the right side of the chest and of the right arm, although his face ap -
peared symmetrical. The right forearm was found to be $1\frac{1}{2}$ inches greater in girth
than the left, the veins on the right side of the chest and of the right arm were more
prominent and distended and the skin of the right arm was warmer than that of the
opposite side (Fig. 7-5a). The abdominal wall was profusely covered in striae,
which seemingly had developed when the patient had reduced his weight abruptly by
dieting some years earlier. The remarkable finding on examination was that the
striae of the right side of the abdomen were convex, those of the left concave (Fig.
7-5b). A vein in the right lower abdominal quadrant appeared distended. There
was a general appearance of heaviness in the abdominal wall on the right, unaf-
fected by posture. Nowhere could pitting be produced on pressure and there were
no areas of discolouration. The swelling was distinctly unilateral and not affected
by gravity in that, although the patient had been lying in bed, there was no tendency
for the swelling to be accentuated in dorsal areas.

No neurological disorder could be detected on full examination, except that the
power of the right arm was distinctly less than that of the left. The pilot stated
that he had noticed this for several months. There were no detectable abnormali-
ties elsewhere with the possible exception of a rather easily palpable liver edge and
splenic tip.

The swelling gradually subsided over the next few days.

The aetiology of this strange disorder remains a complete mystery. It was felt
that there was some chronic obstruction to venous return in the right thoracic inlet
and that perhaps this was exacerbated by altitude; but how? Also, how was one
to account for the abdominal swelling? In association with the possibly enlarged
liver and spleen it was felt that there might well be some reticuloendothelial system
disorder and it was anticipated that a chest X-ray would probably reveal massive
mediastinal glands. In fact the film showed no abnormality. All investigations
proved negative.

138

(a)

(b)

Fig. 7-5 a& b Swelling of the right chest wall and abdominal wall in
Case 20 (from colour transparencies).

The pilot continued to fly, with a restriction not to exceed 25,000 feet and no
further disorder developed. He was killed in a flying accident under conditions in
which altitude sensitivity could not have played any part; the aircraft stalled during
too tight a turn just after take-off. The body was so damaged in the impact that no
post-mortem examination was carried out.

We will never know the aetiology of this case. The only possible explanation one
can offer is that there may have been a gas-containing cyst in the superior part of
the mediastinum, which expanded under reduced pressure, causing obstruction of
venous return. Persistence after descent can only be accounted for by postulating
spasm or possibly thrombosis. How then could one explain the abdominal wall
changes and the long-standing weakness of the right arm?

The only definite conclusion which can be reached is that there was probably some
form of chronic venous obstruction, exacerbated by decompression.

Incidence

How commonly do post-descent phenomena occur?

Surprisingly, hardly any attempt appears to have been made to answer this funda-
mental question. Grulee's eleven cases (1942) occurred in a specified period, but
no mention was made of the number of persons exposed in that time. The same
applied to the full accounts by Masland (1943-1946). Motley et al (1945) did not
record post-descent phenomena at all.

Masland wrote a short paper in 1944 in which he mentioned that there were less than
one hundred serious cases in 800,000 chamber flights. Adler (1950) guessed at
1,000,000 man exposures in decompression chambers in the USA during the 1941-
1945 period and he could find records of about 400 collapse cases, 150 serious.

These data gave incidences of:

Table 7-6   Incidence of post-descent phenomena.   Data of Adler (1950).

'Collapse reactions'	0.04%
Serious collapse	0.015%

Outcome

As has been mentioned earlier, the great majority of cases recover completely,
within a few hours of descent. Some, as exemplified by Cases 17 and 18 are ill
for several days, but almost without exception they recover, probably uninfluenced
by any treatment.

A very few, less than 5% according to Adler's (1950) figures of those showing
serious 'neurocirculatory collapse' have progressed to death. The clinical, clin-
ico-pathological and pathological findings in the severe and fatal cases will be dealt
with in Chapter 8.

8

Severe and Fatal Post-Descent Shock

Clinical Findings

The general observations made so far on the progress of the most serious cases
have been of the simplest nature and no mention has been made of the results of any
investigations more sophisticated than the measurement of the blood pressure.
What additional observations have been made?

Radiography

In several cases the chest has been X-rayed as part of the investigation, generally
to exclude any underlying pulmonary disease. In several cases diffuse patchy con-
gestion or oedema has been revealed, corresponding to the common findings of
basal rales. Cotes (1953) reported a case of a very obese pilot who suffered mar-
ked post-descent shock after a lucid interval following bends, chokes and abdominal
pain at altitude. His chest X-ray showed diffuse, ill-defined areas of increased
density suggestive of patchy oedema. In another case, who vomited whilst uncon-
scious, apart from some diffuse changes, an area of collapse near the apex of the
left lower lobe was seen, presumably due to aspiration.

Goggio (1943) reported on chest X-rays of eleven collapse cases. Seven showed no
abnormality; four had evidence of congestion or oedema. Grulee (1942) noted
apparent basal collapse in one case and increased hilar vascular markings in an-
other. Masland's detailed histories (1943) include two cases showing X-ray evi-
dence of oedema and two vascular engorgement or congestion.

It must be stressed that in all cases of altered X-ray appearances, the films were
taken some hours after the onset of symptoms. In a few instances at Farnborough,
chest X-ray films were exposed either at altitude whilst symptoms were present or
immediately on descent. Abnormalities were never seen.

Temperature

Grulee (1942) did not record the temperature of any of his cases. Masland ap-
peared not to take note of any temperature changes in his early summaries of cases
(1943) and in his analysis of 110 cases (1943) again he did not comment on the fact
that among the ten non-fatal cases he reported in great detail, four showed marked
fever; Case V - 100.6°F 13 hours after onset; case VIII - 105.2°F after 13 hours;
case IX 99.2°F after 6 hours rising to 102°F and case X 103.6°F at 12 hours.

Goggio (1943) tabulated, without comments, data on 135 hospitalised cases.
There were thirty-three cases of fever above 99°F. Adler (1950) made but
passing reference to fever.

Haematology

Grulee (1942) recorded faithfully the available data on his eleven cases of hospitalised decompression casualties. He noted leucocyte counts per cubic mm of 10,000, 12,500, 19,000 and 13,150 in cases 5,7,8 and 9. The red cell counts of cases 7,8 and 9 were also raised, at 5.75, 5.4 and 5.65 million per cubic mm. respectively. He did not comment on the significance of these changes.

Masland (1943) in his earlier report on collapse cases did recognise that white cell counts, haemoglobin, red cell counts and packed cell volume often rose in severe cases. Looking through his case summaries, in those five in which the relevant observations were made, white cell counts per cubic mm. were from 13,500 to 40,300 and the red cell counts in these were over 5.35 million per cubic mm.

Masland, in his second and much more comprehensive report of 1943, commented on the haemoconcentration only. In his case summaries it is clear that haemoconcentration and leucocytosis almost always were present when the blood was examined.

Goggio (1943) took much more interest in the blood changes. So far as haemoconcentration was concerned, he divided his cases into two subgroups on the basis of packed cell volume (PCV) of below or above 55%. The PCV he found to be over 50% in 36 of his 110 cases and over 55% in 27. There were 8 values of over 60%, the highest being 67%. The red cell count he observed to rise proportionately, whereas the white cell count in the majority of the eighty cases in which it rose above 10,000 per cubic mm. had increased disproportionately. In the eight cases of PCV greater than 60%, for example, the average white cell count was 21,550 per cubic mm.

Adler in his summary (1950) mentioned only tersely the blood changes, preferring to deal much more thoroughly with the clinical features, pulse and blood pressure.

A most important part of Goggio's work which has been hitherto almost ignored is his observation of controls. For example, he found no change in PCV in thirty-eight subjects who completed their chamber flights without symptoms. He also made quite clear that blood changes were extremely uncommon in those cases which were rather confusingly called Neurocirculatory Collapse but which occurred at 18,000 feet during hypoxia demonstrations.

In the writer's experience the PCV is almost invariably raised in cases showing post-descent signs or symptoms, particularly pallor, nausea and frontal headache. The only exception among severe reactors was that described previously as Case 20, the man with the bizarre swelling of the arm, chest and belly wall and face.

In the eighteen cases in which the condition of the subject gave rise to anxiety at any stage the findings were as follows:

Table 8-1   Haematological findings in the author's cases.

No change	5	(four of these were very mild and transient; the fifth was Case 20).
Elevated WBC and PCV	8	
Elevated PCV, WBC not taken	2	
Elevated PCV, normal WBC	2	
Elevated WBC, normal PCV	1	

The rapidity with which the blood picture can change is quite remarkable. In one of Cotes' (1953) cases, the PCV was 60% within four hours of the onset of symptoms and in fatal cases (described later) even more remarkable changes have been seen. The leucocytosis is almost always purely due to an increase in neutrophils.

The Erythrocyte Sedimentation Rate is rarely raised.

Blood Chemistry

In those cases in which blood chemistry has been examined no consistent change has been observed. In one case only an abnormally high potassium level was detected - 7.2 mEq/L in the plasma. This may well have been due to a minor degree of haemolysis. No elevation of serum protein or disturbance of albumin:globulin ratio has been detected.

In two cases which the writer has seen serum transaminases were found to be at normal levels. Berry (1960) also found a normal SGOT in one of his cases.

Blood Volume

To the writer's knowledge, only twice has any attempt been made to assess blood volume during post-descent shock. As a result of discussion with a clinical colleague it was decided that such an estimation would be of great interest and therefore the Coomassie Blue technique was applied to two cases admitted to an R.A.F. Hospital in 1960 (Kelly, personal communication).

Case 21

A 28 year old pilot 70 inches tall, weight 177 lb, was submitted to an exposure in a decompression chamber to a simulated altitude of 28,000 feet. He had an undisclosed history of many episodes of bends in flight. After 100 minutes he complained of pain in knees, wrists and shoulders. His right arm began to feel numb and his vision became blurred. Descent relieved the symptoms except for the visual defect, but he developed a headache, slight mottling of the skin and malaise. He recovered rapidly on admission to hospital. His blood investigations showed no notable abnormality; his haemoglobin was 111%, his PCV 48% and his total white cell count 4,800 per cu. mm.

His plasma volume estimation by the Coomassie blue dye technique was 3.7 litres. Ten days later a repeat estimation gave a value of 4.0 litres.

This result can probably be regarded as within normal variation. It is not surprising in view of the lack of other signs of circulatory disturbance.

Case 22

This 31 year old pilot, 70 inches tall and 187 lb in weight, suffered from bends in the right knee and left shoulder during a 28,000 foot chamber run. He also developed severe abdominal pain. On descent he felt much better, but not completely so.

He showed marked mottling of the skin of the chest, extending into the right axilla. His haemoglobin was estimated at 121%, PCV 53%, white cell count 14,000 per cu. mm. and his rectal temperature was 99.0°F. His plasma volume was assessed by the Coomassie Blue method and was found to be extremely low, 2.5 litres. A week later a repeat of the same method gave a value of 4.2 litres, within the normal range.

It will be noted that the indicated reduction of plasma volume is quite out of proportion to the rise of packed cell volume. It can only be assumed that a large part of the apparent reduction in circulating plasma must have been due either to a very sluggish mixing of the injected dye and the blood, incomplete at the time of sampling, or a sequestration of blood, temporarily completely cut off from the circulation. Probably both factors played a part. The skin mottling may be an indication of wide-spread circulatory stasis.

Urine

No consistent urinary changes have been observed. The urine volume is generally greatly reduced during the acute phase, to be followed by a diuresis during recovery. The concentrated urine of the acute phase often contains albumen and a few blood cells. In one case investigated by a clinical colleague (Cooke, 1961, personal communication) a twice-normal urinary creatinine excretion of 1.19 gm. in the first twenty-four hours was felt to reflect tissue damage.

Cerebrospinal Fluid

In a number of cases lumbar puncture has been performed. Indeed Halbouty and Long (1953) were of the opinion that lumbar puncture was an important part of therapy. In a series of fourteen examinations culled from the literature the writer can find little evidence of abnormality. The pressure has rarely been raised and very few cells have been found. The protein level is, however, sometimes elevated as is the glucose level.

Fatalities

Much of our knowledge of disease processes is the result of assiduous examination of fatalities. Pathology gives the clinician the evidence of the end-result of the disease process and the body's defensive reactions. Often the two are difficult to disentangle, but at least in the majority of diseases the basic lesions if not the causative organisms become identified and the background to the clinical picture becomes apparent. Decompression sickness should be no exception, but most unfortunately the results of investigation of fatalities have been far from revealing.

The literature in which fatalities have been reported is scattered and confusing, some individual deaths having been reported and reviewed many times under different names and reference numbers. The most comprehensive review seems to have been that attempted by the writer (Fryer, 1962) in which the cases were arranged chronologically and where possible, identified by initials.

In order to give a clearer picture of the fatal case the world series of seventeen is reviewed here in summary. It is with reservations that the histories are repeated, but any attempt to tabulate such diverse features as are necessarily significant leads to an impossible jungle of figures and separation of history from clinical pathology, morbid anatomy, histology, etc. renders analysis slightly easier only at the price of complete disjointedness.

The summaries which follow may seem to differ in some respect from the original sources. In fact, thanks to the extreme generosity of the Director of the US Armed Forces Institute of Pathology and others, the writer has been privileged to survey to original protocols, to examine the sections and in all but two of the cases, to acquire full sets of sections for full study by any relevant technique. Errors in transcription in the original papers have thus, it is hoped, been corrected so far as histories and autopsy protocols are concerned. Regarding the histo-pathology,

the writer is not a practising morbid-pathologist, but hopes that by careful study of
the material and discussion with colleagues he has been enabled to interpret the find-
ings correctly, to put minor changes into perspective and to bring up to date early
cases in the light of subsequent investigations. In general, many of the cases have
never been reviewed as a series except by the neuropathologist, Haymaker, who
naturally concentrated on the nervous system appearances.

Histories are sub-divided on the basis of decompression chamber and in-flight
occurrence.

Chamber Cases

Fatality 1   R. F. K.   22 April, 1943.   USA.   Time to death 8½ hours.   Masland
(1943) case 1; Masland (1944), case 1; Goggio and Houck (1945) case 5;
Haymaker and Davison (1950) case 1; Adler (1950) case 1; Haymaker (1957)
case 1.   AFIP Accession Number 95412.

History   A heavily-built cadet aged 25 years.   Decompressed to 38,000 feet at
approx. 1700 hours.   Complained of nausea and dyspnoea after 72 minutes.
Collapse was imminent.   At 1715 (ground level), cold clammy. pulse 54. respira-
tion 32. B. P. 90/60.   Allowed to leave the vicinity of the chamber at 1755.   At
1800 he complained of weakness, breathless and nausea.   He vomited and became
shocked, cold and clammy. pulseless. blood pressure unmeasurable, respirations
35/min.   At 2115 he felt increasingly hot; nauseated but unable to vomit.   By 2330
cyanosis had become very marked.   At 2400 he was restless and apprehensive, but
still lucid.   He complained of chest pain; pulmonary oedema developed and died
at 0130 on 23.4.43.

Treatment   Oxygen and 450 ml fluid by mouth.

Necropsy Findings   (8½ hours after death)

Heavy built. muscular, slightly obese.

Lungs - 650 ml fluid, turbid and fibrin-flecked in each pleural cavity.   Weight 907
      gm.

Heart - 150 ml bloody pericardial effusion.   Heart weighed 350 gm.   Both sides
      dilated.   Blood syrupy.

Gut - Congested stomach.   600 ml fluid contents.

Liver - 1635 gm.   Engorged.

Kidneys - Extremely congested.

Spleen - 228 gm.

Thymus - 27 gm, fatty.

Thyroid - Normal.

Adrenal glands - Together 12.5 gm.

Bone Marrow - Congested with petechiae.

Brain - Engorged meningeal vessels.

Histology   (Fig. 8-1)

Lungs - Congestion, marked oedema, very light fat embolism.

Heart - Within normal limits.
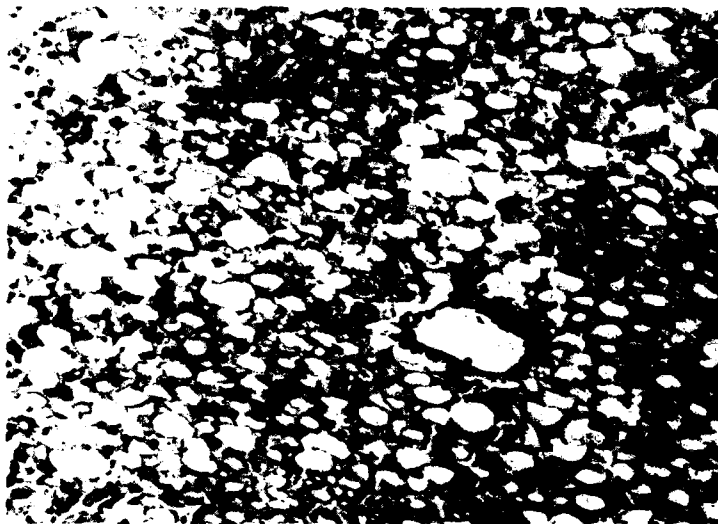
Fatality I

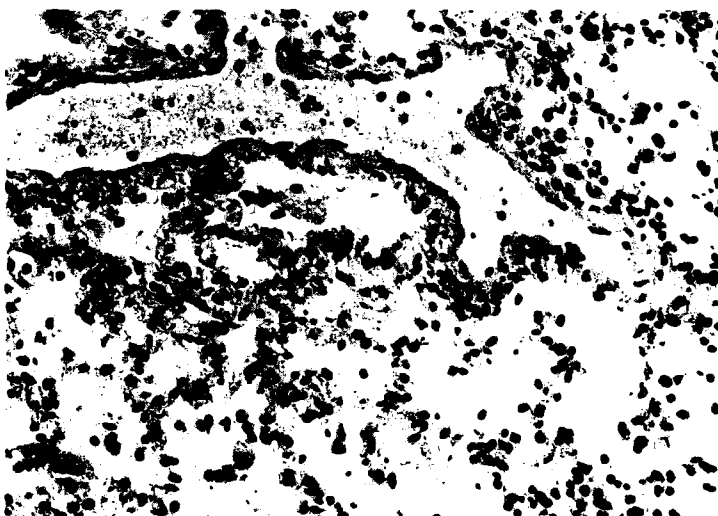Fig. 8-1 (a)   R.F.K., liver, H. & E. x 130.

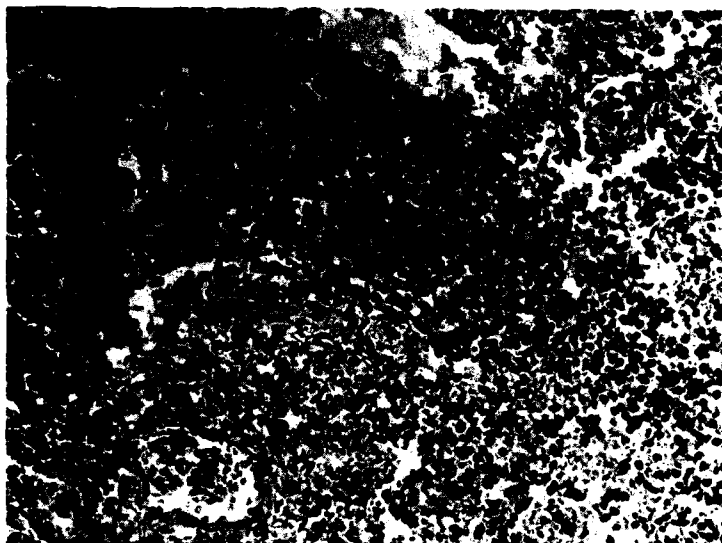Fig. 8-1 (b)   R.F.K., lung, H. & E. x 130.

Fatality II

Fig. 8-2 (a)   H.E.P., lung, H. & E. x 185, showing broncho - pneumonia.
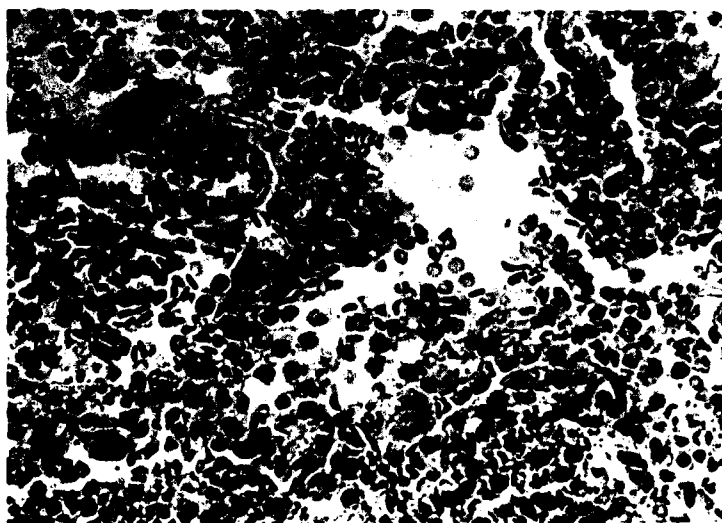

Fig. 8-2 (b) H.E.P., lung, H. & E. x 375, showing haemorrhage and
inflammatory exudate.

Liver - Fatty vacuolation with ceroid deposits, heavy in one block, moderate in the
    other. Congested. Mild inflammatory change in some portal tracts.

Kidney - Very congested, particularly vasa recta. Rather advanced autolysis of
    proximal tubular epithelium. No fat embolism.

C.N.S. - (Haymaker and Davison, 1950). Mild ischaemic changes scattered
    throughout the brain. No fat embolism.

Fatality II H.E.P. 15 June, 1943. USA. Time to death 71 hours. Masland
(1943), case 11; Masland (1946), case 7; Masland (1948), case 3; Moon
(1948); Haymaker and Davison (1950), case 5; Adler (1950), case 2; Haymaker
(1957), case 5. AFIP Accession Number 100893.

History Twenty-six year old pilot, about 23 lb overweight, decompressed at 2,500
ft/min. to 38,000 feet. Early mild abdominal discomfort, bends in wrist at 35 min.
followed by pallor and rapid deep breathing. Possible weakness of right arm.
Descent after 35 min. A few minutes later right arm became weak and subject
sweated profusely. B.P. 100/60, pulse 60. Blood taken at 2 hours after first
symptoms: PCV 55%; 3 hours later PCV 56%; white cells 20,200 cu. mm. Hae-
matocrit rose progressively to 65%. Became drowsy, irrational and hyperpyrexic
(reaching 108.4°F) cyanosis, vomiting, vertical nystagmus and right hemiparesis.
Coma became deeper, blood pressure remained good until the last. Finally died
after some 71 hours.

Treatment

First 24 hours. Oxygen, 2 L plasma. 1 L subcutaneous saline, stimulants, ice
packs.

Second 24 hours. Tracheotomy, helium 80%: O_2 20%. 4 L fluids (mostly glucose
saline), 20 ml adrenal cortical extract, digitalis, chloral, etc.

Third 24 hours. He:O_2 mixture, 3 L fluids, stimulants.

Necropsy (8 hours after death).

Well nourished, 72 in, 184 in.

Lungs- Trachea and bronchi injected. Pleural cavities dry, lung bases congested
    and oedematous.

Heart - 30 ml pericardial straw-coloured effusion. Normal.

Gut - Normal.

Liver - Somewhat swollen, congested.

Kidneys - Swollen and congested.

Other organs - Normal

Brain - Somewhat swollen, moderate meningeal congestion.

Histology

Lungs - Extreme congestion and oedema. Moderate fat embolism was reported in
    the original examination. Some patches of haemorrhage and collapse.
    Areas of bronchopneumonia developing (Fig. 8-2).

Heart - Minimal evidence of early muscle fibre necrosis with no cellular reaction.
    Some oedema.

Liver - Very congested with moderate *centrolobular fatty vacuolation* (Fig. 8-3).

Kidney - Congested with much precipitated material in the glomerular capsular spaces and tubules. Very numerous hyaline casts. Tubular cells, particularly of the distal and collecting regions, show advanced degenerative changes (Fig. 8-3). No fat emboli seen.

Spleen - Normal.

Adrenals - Congested with depleted lipid in the outer zones of the cortex.

C. N. S. - Reported by Haymaker and Davison (1950) to show minor localised areas of oedema and demyelination, scattered through the cortex. A few small perivascular haemorrhages.

Fatality III   D. H. G.   16 September, 1943.   USA.   Time to death 16¾ hours. Haymaker and Davison (1950) case 2; Adler (1950) case 3; Haymaker (1957) case 2.   AFIP Accession Number 103767.

History   A stocky 22 year-old, approx. 29 lb overweight. Decompressed to 38,000 feet. After 85 minutes complained of dizziness and diplopia. No other symptoms. On descent weakness supervened and scintillating scotomata were reported. Pale, clammy and 'mildly shocked' in hospital 1¼ hours later; improved but fainted in latrine 4½ hours later. Became profoundly shocked B. P. 66/0, pulseless, vomiting repeatedly, pulse rose to 138/min., resp. to 34/min., temp. to 103°F. Became very restless, cyanosed and sweated profusely with severe abdominal pain. Died 16¾ hours after original symptoms. No laboratory investigations reported.

Treatment   250 ml plasma, oxygen, 3 ml adrenal cortical extract, stimulants, 1/8 gr. morphine.

Necropsy   (7 hours after death).

Stocky build.

Lungs - 600 ml straw-coloured fluid in each pleural cavity. Lungs 'boggy'.

Heart - Pericardial effusion 5 ml. Right atrium moderately dilated.

Liver - Moderately congested.

Kidneys - Moderately congested.

Histology   (Fig. 8-4)

Lungs - Reported by Haymaker and Davison to be very congested and oedematous, with scattered fat emboli.

Heart - Within normal limits.

Liver - Moderately severe fatty change. Very congested.

Kidney - Extremely congested, including the glomerular tufts. Very poor preservation of proximal tubule cells.

Adrenals - Reported by Haymaker and Davison to be normal.

C. N. S. - Some ischaemic changes in the cortex and congestion elsewhere reported by Haymaker and Davison.
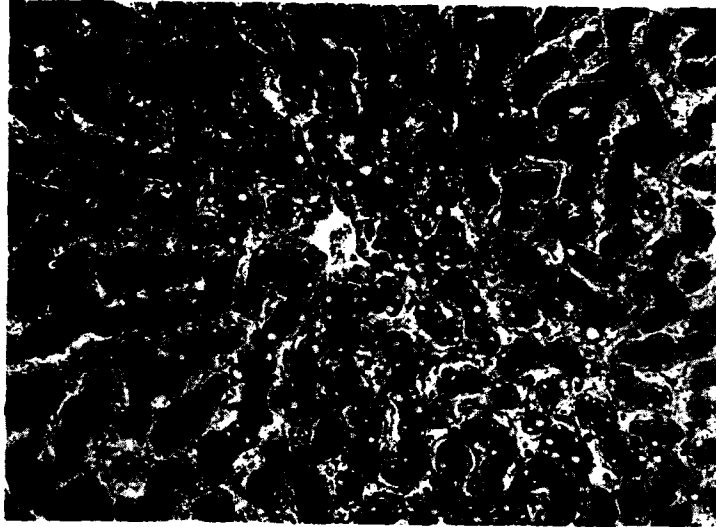
Fatality II

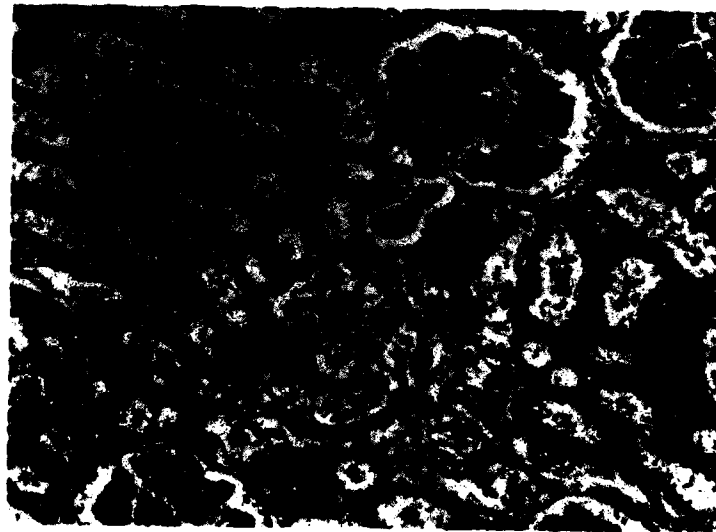

Fig. 8-3 (a)   H.E.P., liver, H. & E. x 185.

Fig. 8-3 (b)   H.E.P., kidney, H. & E. x 130.
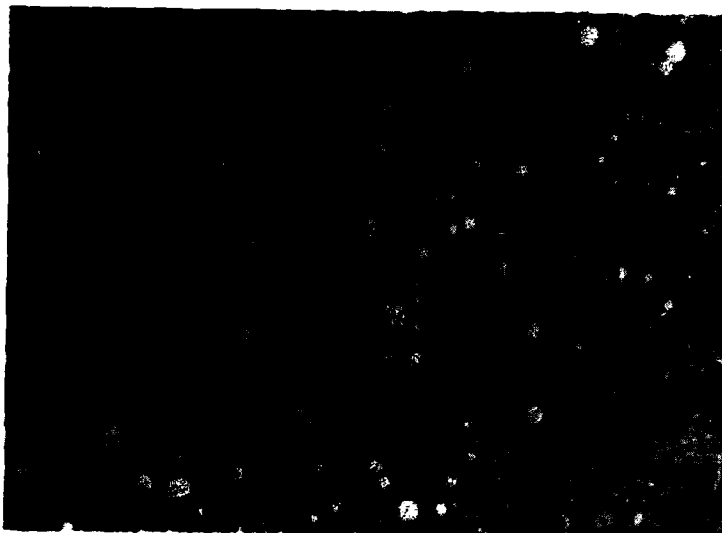
151

Fatality III

Fig. 8-4(a) D.H.G., liver, H. & E. x 130.

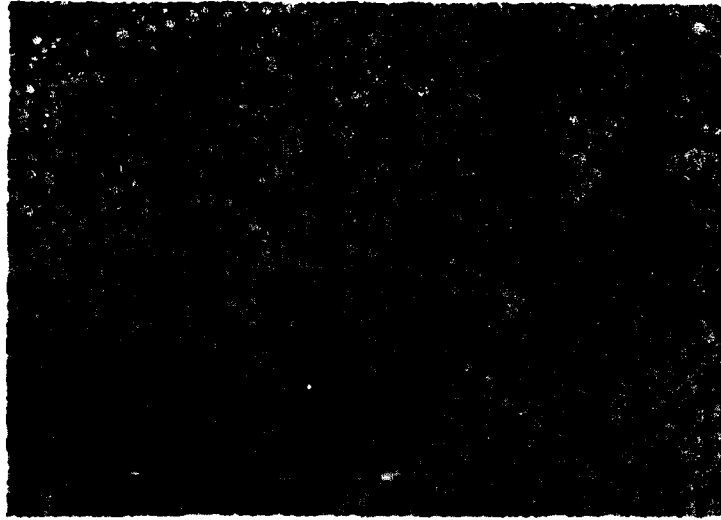Fig. 8-4(b) D.H.G., kidney, H. & E. x 130.

Fatality IV

Fig. 8-5 (a)   E. R. T., liver, H. & E. (photo by courtesy of U. S. AFIP).

Fig. 8-5 (b)   E. R. T. kidney, H. & E. x 130.

Fatality IV E. R. T. 28 October, 1943. USA. Time to death $17\frac{1}{4}$ hours.
Masland (1943) case 12; Moon (1948); Haymaker and Davison (1950) case 3;
Adler (1950) case 4; Haymaker (1957) case 3. AFIP Accession Number
100822.

History A 38 year old senior officer carried out, without complaint, a decompre-
ssion training run in the morning of 28th October, 1943, and another in the after-
noon. In the latter, having been at 30,000 feet for no more than 29 minutes he felt
bends in both knees, but lasted out another 31 minutes. After this hour at 30,000
feet, ascent was resumed to 38,000 feet but before that level could be achieved his
bends became very severe, he developed chokes and descent was necessary. He
had transient diplopia, weakness and tingling of the right arm and profuse sweating.
These rapidly resolved after a few minutes at ground level, but he felt weak and was
slightly cyanosed. He became restless one hour after admission to hospital and
obviously was developing pulmonary oedema. His abdomen became distended and
he started to vomit. His B. P. fell to 90/0 and his pulse rose to 140/min. He
sweated profusely and became progressively weaker although lucid until he died $17\frac{1}{4}$
hours after the onset of symptoms.

A blood sample taken 1 hour 40 minutes after descent showed haemoconcentration to
a PCV of 60% and a white cell count of 23,000/cu. mm.

Treatment During his illness, this patient was given oxygen, 1 L of plasma, a
mercurial diuretic, theophylline, stimulants and two doses of 1/6 gr. morphine.

Necropsy ($2\frac{1}{2}$ hours after death).

Obese (220 lb, height not given), much older in appearance (50+) than actual age of
38 years.

Lungs - 750 ml straw-coloured fluid in each pleural cavity. Left lung 742 gm.
        Right 850 gm. Congested and oedematous.

Heart - 10 ml pericardial effusion. Heart 410 gm, contracted.

Gut - Haemorrhagic patches in stomach, duodenum and most of small bowel.

Liver - 2395 gm congested.

Spleen - 220 gm.

Kidneys - 380 gm.

Adrenals - Congested.

C. N. S. - Vessels engorged.

Histology (Fig. 8-5)

Lungs - Most surprisingly the alveoli appeared dilated and air-filled. No fat emboli.

Heart - Slight oedema and fibre necrosis reported.

Liver - Severe centrolobular fatty necrosis.

Kidney - Very congested. Tubules autolytic. No fat emboli.

Adrenals - Normal.

C. N. S. - A single area of myelin rarefaction in sub-cortical white matter. A few
           small fat emboli. Moderate numbers of small perivascular haemorrhages.
           The spinal cord in cervical and upper thoracic regions showed striking
           haemorrhages in the white matter and disintegrative changes in the grey
           matter (Haymaker and Davison, 1950).

Fatality V   C.S.   30 May, 1944.   UK.   Time to death 13-14 hours.   Briefly
mentioned by Sproull (1951);   Fryer (1956);   Fryer (1962).

History   Pilot, age 28, fit and keen.   Decompressed on 30th May, 1944, to
37,000 feet for 2 hours. Did not confess to any symptoms but was seen to sit with
head supported by hands, to be pale and was described subsequently as having been
'slightly collapsed'.   Some 15 minutes after descent he had a momentary attack of
feeling muzzy with slurred speech.   Felt unwell generally, retiring to bed early.
Colleagues noted him to behave hilariously, as though drunk.   Complained of whee-
ziness, saying 'Listen to me breathe I feel as if I have only got one lung.'   He
complained also of nausea.   He seemed to recover somewhat, but his room mate
noticed him to have a restless night and he was heard to hasten from the room at
about 0530 hours.   He was found dead on the lavatory floor at 0720.

Necropsy   (approx.   30 hours after death).

(Details kindly provided by Professor A.C. Campbell)

Well-nourished.   Slight oedema of legs.   Bluish lividity of dependent parts.

Lungs - 900 ml pinkish fluid in each pleural cavity.   Heavy and oedematous.

Heart - 15-20 ml pericardial fluid.   Heart normal size, slight dilatation of right
        ventricle.   Petechiae on right side of septum.   Septa intact.   Blood very
        viscid.

Gut - Few petechiae in stomach.

Liver - Deeply congested.

Kidneys - Congested with prominent stellate veins.

Spleen - Normal.

Thymus - 34 gm.   Enlarged, possible oedematous.

Thyroid - Congested.

Adrenals - Left 4.5 gm; right 5 gm.   Small yellow hyperplastic areas in cortex,
        otherwise normal.

Bone Marrow - Normal.

Brain - All vessels congested.

Histology   (from original report by Professor A.C. Campbell and review of re-cut
material).   (Fig. 8-6)

Lungs - Oedematous and congested.   Very numerous alveolar cells.

Heart - Congested with sludging of white cells.   Slight brown atrophy.   One focus
        of white cell diapedesis seen.

Liver - Congested with an area of fatty vacuoles of large size.   Some fine vacuoles
        with eosinophilic inclusions.

Kidney - Extreme congestion, particularly of afferent arterioles (identified by ela-
        stic lamina).   Very gross autolytic change.

Spleen - Normal.

Adrenal - Some bleeding into capsule and one tiny haemorrhage in cortex.
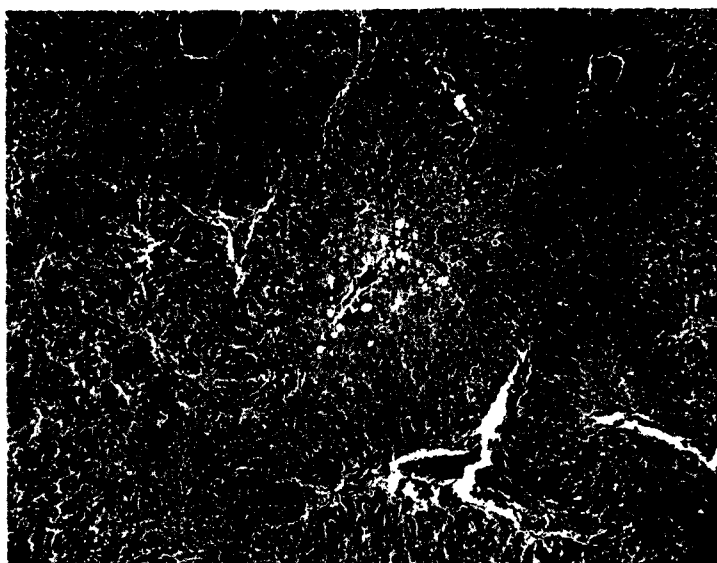
Fatality V

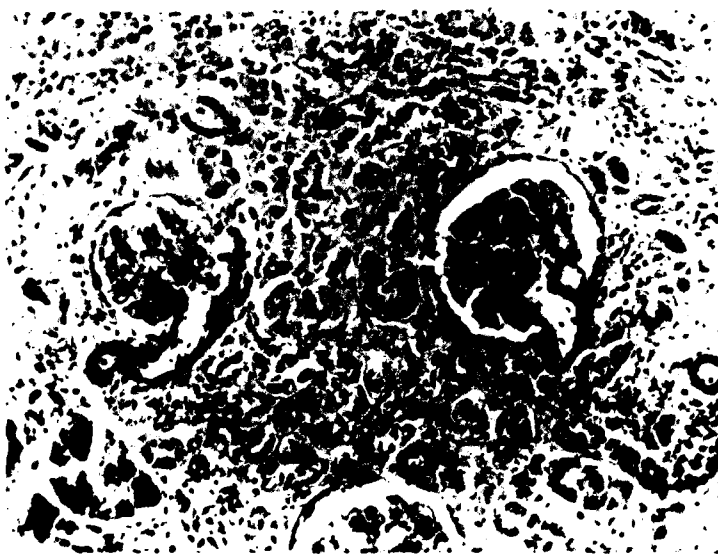Fig. 8-6 (a)   C.S., liver, H. & E. x 40.

Fig. 8-6(b)   C.S., kidney, Heidenhain's iron haematoxylin, x 130.
Note afferent dilatation.

Pituitary - Congested.

Bone Marrow - Normal.

C.N.S. - Normal in all respects other than congestion.

Fatality VI   G.J.B.   28 June, 1944.   USA.   Time to death 38½ hours.   Masland (1948) fatal case 1:   Adler (1950) case 5;   Haymaker (1957) case 6.   AFIP Accession Number 113646

History   Airman, age 22, approx. 18 lb overweight.   Decompressed on 28th June 1944, to 30,000 feet.   He subsequently told colleague that his left leg was stiff. After 19 minutes at 30,000 feet, pale, nauseated, coughing.   Lost consciousness. convulsed and possibly suffered cardiac arrest for some 15 seconds.   Sweating and coughing on way to hospital, but becoming more rational.   Two hours later speech was difficult, right arm weak and clumsy;   became delirious and very irritable. Vomited and was incontinent.   B.P. about 130/90.   Respiration rapid and deep. PCV reached 55%, red cells 6,150,000/cu. mm. white cells 29,850/cu.mm.   He continued in a comatose state, with bouts of sweating and pyrexia to 106.2°F (rectal) Pulmonary oedema and cardiac irregularity supervened and he died approximately 38½ hours after the first symptoms.

Treatment   Oxygen, 90% O_2: 10% CO_2, parenteral fluids - plasma 4L, saline, glucose etc. 4L.   Adrenal cortical extract 195 ml 50% glucose 50 ml.   Alcohol sponging, thiamine chloride 50mg.

Necropsy   (delay unknown).

Well built.   Cyanosis of extremities.

Lungs - Pleural cavities dry.   Lungs 850 gm each.   Marked congestion and oedema

Heart - 75 ml pericardial effusion.   Heart 350 gm, small epicardial haemorrhages.

Gut - Scattered haemorrhages.

Liver - 1700 gm.

Kidneys - Left 200 gm, right 175 gm.

Brain - 1730 gm.   Congested and swollen.

Spinal cord - Normal

Histology   No reports in the literature or in the files of US Armed Forces Institute of Pathology.   No material traced.

Fatality VII   A.P.H.   15 December, 1944.   USA.   Time to death 55½ hours. Masland (1948) fatal case 2;   Adler (1950) case 6;   Haymaker and Davison (1950) case 4;   Haymaker (1957) case 4.   AFIP Accession Number 127451.

History   Officer, age 23, approx.   28 lb overweight.   Decompressed to 30,000 ft on 15th December 1944.   After 21 minutes sweaty, dizzy and coughing.   Collapsed within 2 minutes, sweating profusely.   Incontinent of urine.   Regained consciousness at ground level, but could not speak.   Apparent left hemiplegia.   Coughing

and dyspnoeic. On admission 45 minutes after onset, unconscious, respiration 45/min., B.P. 100/80, pulse 120. Cold and clammy, mottled, hyperactive reflexes on left. Sudden apnoea at about 4 hours, respiration restored by resuscitation. B.P. fell 90/0, to improve later to 112/80. Temperature rose to 103°F (rectal). Vomited. At 18 hours after onset PCV 57%, white cells 20,000/cu. mm. Later progressed to coma with convulsions, hyperpyrexia to 107.6°F, blood pressure of 120/80-160/80, but pulse of 170-180/min. Died about 55½ hours after onset.

Treatment   Oxygen, 3,375 ml parenteral fluids. Stimulants.

Necropsy   (12 hours after death).

Slightly obese. Mottled over face, neck, abdomen and upper thighs.

Lungs - 30 ml fluid in each pleural cavity. Lungs: left 935 gm, right 850 gm. Dark, congested and oedematous with numerous surface petechiae.

Heart - 20 ml clear pericardial effusion. A few pericardial petechiae. Heart 397 gm.

Gut - Numerous petechiae in stomach.

Liver - 1673 gm.

Spleen - 160 gm.

Kidneys - Congested. Left 156 gm, right 142 gm.

Adrenals - Total 25gm.

Brain - 1424.5 gm. Injected appearance.

Histology   (Fig. 8-7)

Lungs - Congested and oedematous. Some bronchopneumonia. A few fat emboli reported (Haymaker and Davison). One organising fibrinous plaque seen within a pulmonary artery branch.

Heart - Normal but for fine fatty deposit in the medial muscle fibres of coronary arteries.

Liver - Moderate congestion and centrolobular fatty change.

Kidney - Congested. Fairly well preserved.

C.N.S. - Minor ischaemic changes in neurones.

Fatality VIII   G.W.H.   6 January 1950.   USA.   Time to death 45 hours.   Adler (1950) case 7; Haymaker (1957) case 7.   AFIP Accession Number 293075.

History   33 year old N. C. O., approx. 22 lb overweight. This man had undeclared neurological sequelae to a decompression to 35,000 feet in mid-December 1949. These had been intermittent sensory and motor defects in the left limbs, weakness and anorexia. Decompressed on 6th January, 1950 to 40,000 feet where he developed bends in shoulders and knees, sweating and pallor. He hyperventilated and collapsed some 8 minutes after reaching altitude and an immediate descent was carried out. He recovered partially, remaining disorientated, with a lessening left hemiparesis. Soon after admission to hospital, he became hyperactive, maniacal and then unconscious. B.P. at this time was 135/80, pulse 110/min.
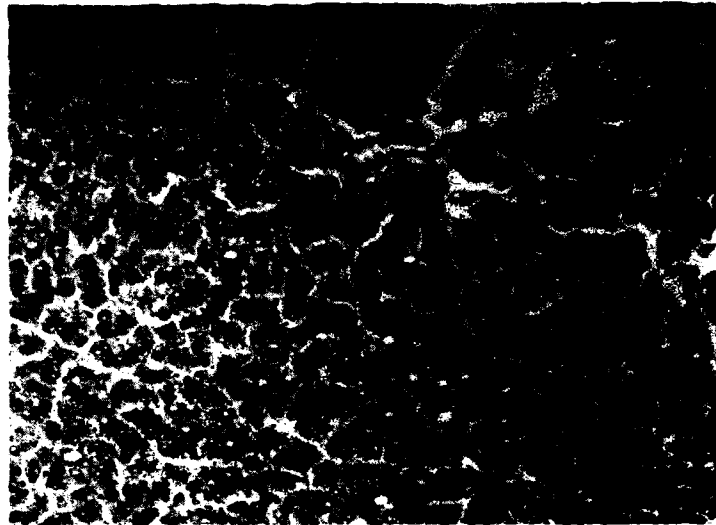
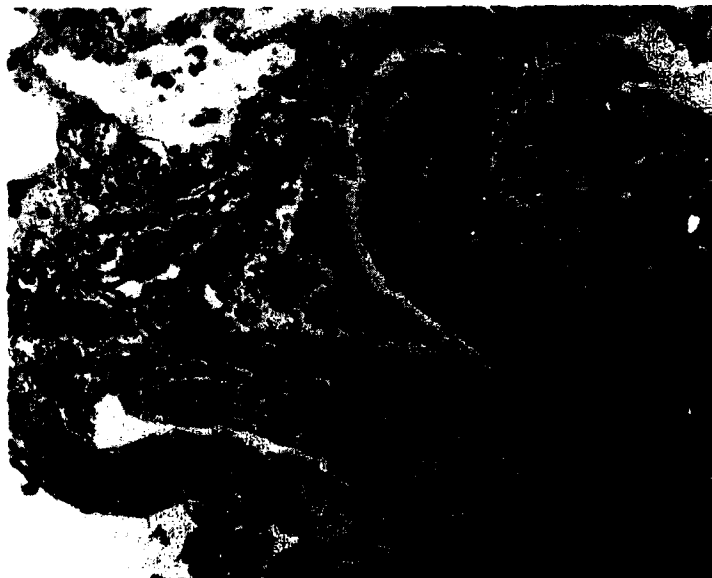Fatality VII

Fig. 8-7 (a)   A.P.H., liver, H. & E. x 130

Fig. 8-7 (b)   A.P.H., lung, H. & E. x 185, showing organised fibrinous plaque in arterial wall.
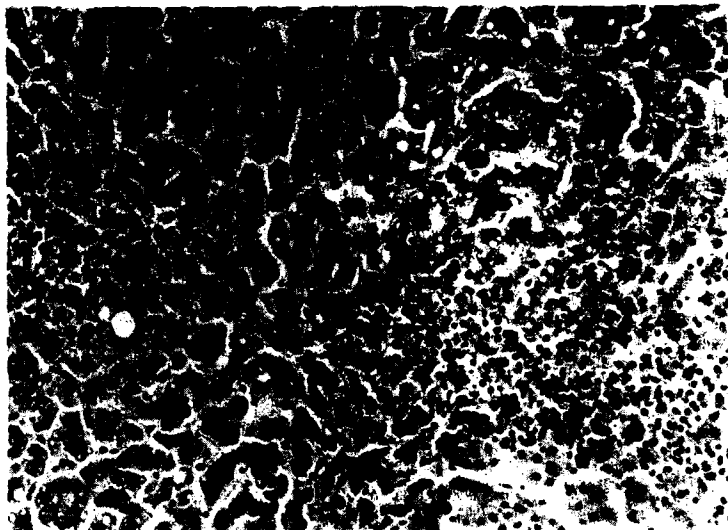
Fatality VIII

Fig. 8-8 (a)   G. W. H., liver, H. & E. x 130, showing focal inflammatory change.
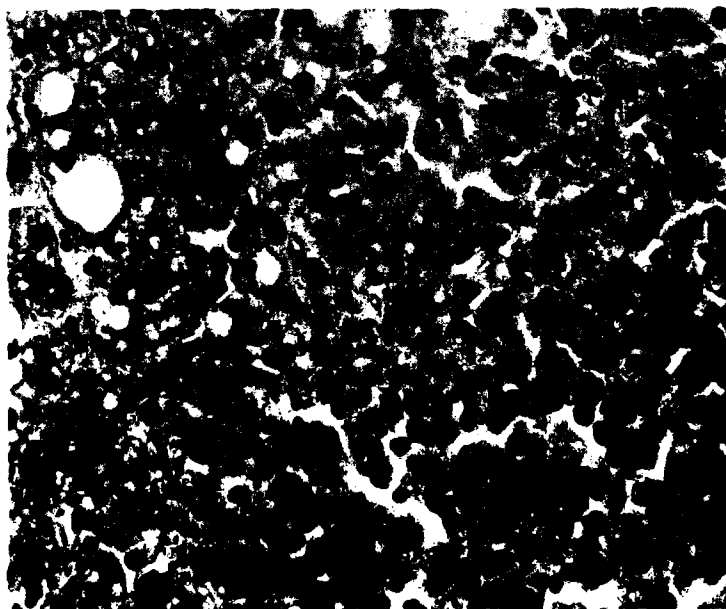

Fig. 8-8 (b)   G. W. H., liver, H. & E. x 375, showing detail of focal necrotic area.

His temperature rose steadily to 105°F, his coma deepened, respiration became rapid and he finally died some 45 hours after the initial symptoms. He showed no haemoconcentration, but a white cell count of 10,800/cu. mm.

Treatment   Oxygen, 1 L plasma, 0.5L saline, paraldehyde, papaverine, aminophylline, calcium gluconate, ice packs.

Necropsy (time unknown).

Very well developed and nourished.

Lungs - 300 ml brown fluid in left pleural cavity, probably from terminal stomach perforation.   Lungs congested and oedematous with subpleural petechiae. Left 350 gm, right 650 gm.

Heart - 35 ml turbid yellow pericardial effusion.   Multiple subendocardial haemorrhages in left ventricle.   Right heart dilated.   The prosector later recalled that the septa were almost certainly intact.

Gut - Terminal stomach perforation.

Liver - 1950 gm.

Brain - Diffuse swelling behind the left calcarine fissure.   Slight 'coning' of the brain.

Histology   (hitherto unpublished)   (Fig. 8-8)

Lungs - Congestion, oedema and haemorrhage.   Severe autolysis.

Heart - Congestion only.

Liver - Intensely fatty, particularly centrolobular.   Very congested.   Some areas of necrosis.

Kidneys - Congested.   Some tubules rather dilated.   One possible site of a dissolved-out fat embolus seen.

Adrenals - Normal.

Bone Marrow - Normal.

C.N.S. - (Haymaker & Johnston, 1955).   Large scattered foci of ischaemic type, similar to two in-flight cases described below (XII and XIII).

Fatality IX   J.D.   24 October 1951.   UK.   Time to death 5¼ hours.   Cotes (1953) case 3;   Haymaker (1957) case 9.

History   A 37 year-old airline steward, approx.   29 lb overweight.   Decompressed to 25,000 feet for approximately 25 minutes then taken in 4½ seconds to 40.000 feet.   Almost at once he became pale, coughed, complained of pain in the right upper chest and collapsed.   Immediate descent caused dramatic relief of symptoms. At ground level he felt completely well and appeared normal.   B.P.   140/100. Thirty-five minutes later he felt jittery looked pale and developed a mild headache. Rapidly he went into profound circulatory collapse with nausea, sweating and anxiety.   Incoherent, pulseless, cyanosed.   Vigorous treatment for haemoconcentration (blood taken 1 hour after onset of collapse showed a PCV of 65%) and administration of pressor agents gave transient improvement, but the PCV rose to 69% and he died 5¼ hours after the initial reaction at altitude.   Numerous investigations on blood, CSF and urine were reported by Cotes.   The white cell count was 17.000/cu. mm.

Treatment   Oxygen, binding of the elevated limbs. Noradrenaline 4 ml of 1 : 1 000 sol, paraldehyde, approx.   600 ml saline.

Necropsy   (14 hours after death).   The examination was carried out by Professor W. Blackwood, who kindly in discussion enlarged on his written report and also made available preserved specimens of the tissues.

Rather obese, with marked post mortem lividity of the upper half of the body.

Lungs - 350 ml clear fluid in left pleural cavity.   370 ml in right.   Left lung 460 gm, right lung 550 gm.   Both congested and oedematous.

Heart - 320 gm.   Numerous recent endocardial haemorrhages in the left ventricle. Examination of the fixed specimen in 1956 (by the writer) revealed valve-guarded patency of the atrial septum with a communication of approximately 6.5 mm x 2 mm (Fig. 8-9).

Gut - 300 ml undigested food in stomach.   Normal.

Liver - 1340 gm.   Firm yellowish-brown liver with signs of engorgement.

Kidneys - Left 130 gm.   Congested.   8 mm caseous nodule in the cortex.   Right 120 gm, congested.

Spleen - 180 gm.   2 mm x 4 mm caseous nodule.

Thyroid - Normal.

Adrenals - Left 6.1 gm.   Right 6.7 gm.   Healthy in appearance.

Genitalia - Numerous chronic abscesses of left testis.

Brain - C.S.F. slightly brown (blood-stained at lumbar puncture before death). Congested brain.

Histology   (Fig. 8-10)

Lungs - Congestion and oedema.   Occasional unequivocal fat emboli.

Heart - Small subendocardial haemorrhages and one small interstitial haemor-rhage.   Faint fat deposit in coronary artery branch muscle layer in some sites.   No atheroma.

Liver - Very congested with marked fatty vacuolation.

Kidneys - Congested with engorgement of some glomeruli.   Marked autolysis or necrosis of tubule cells.   Mild arterio-sclerotic changes.

Adrenals - Normal.

C.N.S. - (Professor W. Blackwood's report).   "No significant abnormality other than congestion and rather numerous polymorph leucocytes in vessels.   Spinal cord normal."   On re-examination of material including frozen sections of the choroid plexus, no fat emboli were found.

Fatality X.   Canadian Case.   Date uncertain.   Time to death 17 hours.   Reported by correspondence by Stewart to Haymaker, who included this case as No. 10 in the 1957 paper.   No further details have been found, despite enquiry.

History.   A 28 year-old man of average build.   Apparently suffered bends and possible chokes after 1 hour 50 minutes at 35,000 feet.   Descent 10 minutes later, followed after a $2\frac{1}{4}$ hour lucid period by respiratory and visual disturbances, pro-gressive shock and death.

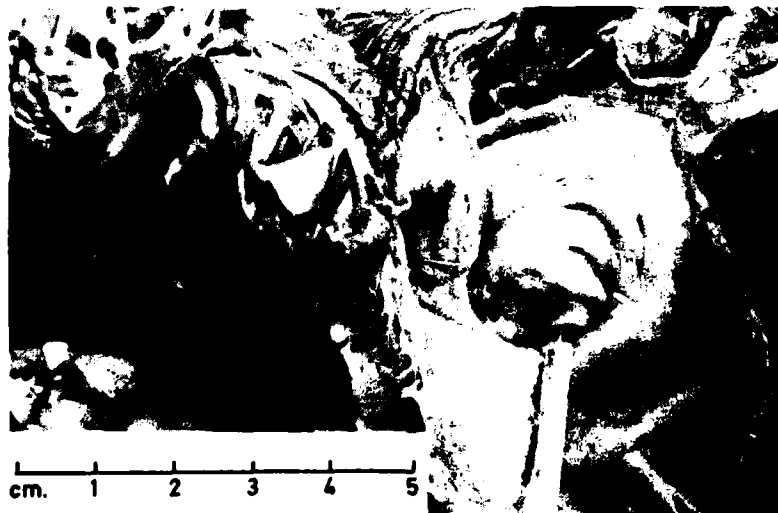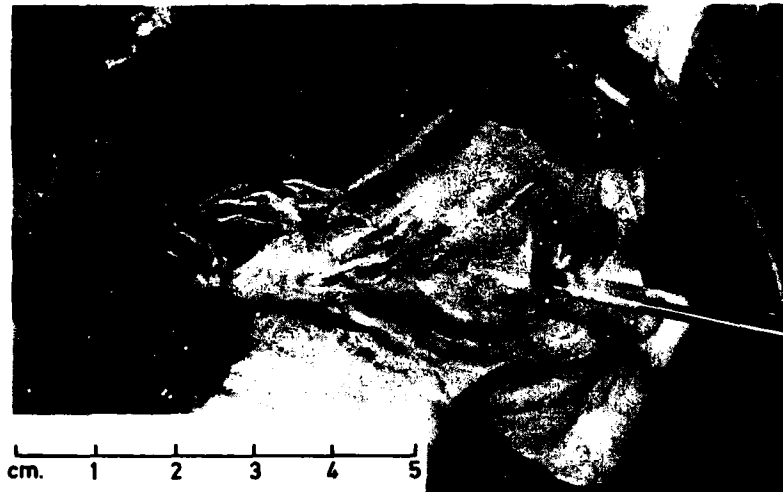Treatment   No details available.

Fatality IX

Fig. 8-9   J.D., heart (fixed).   Probe through patent foramen ovale,
seen from left (above) and right (below).
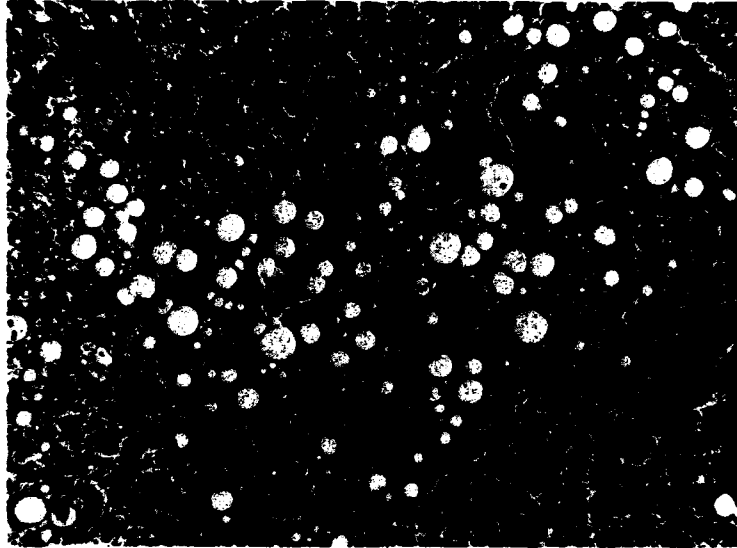
Fatality IX

Fig. 8-10 (a) J.D., liver. Heidenhain's Iron Haematoxylin x 110.
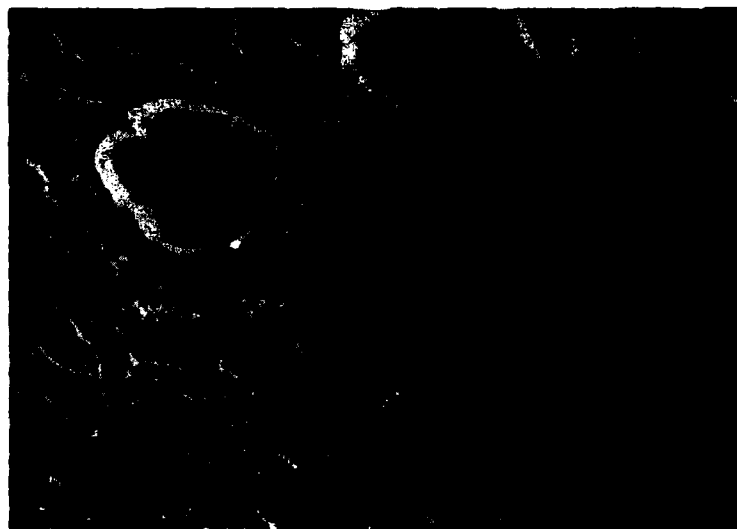

Fig. 8-10 (b) J.D., kidney. Van Gieson x 150.
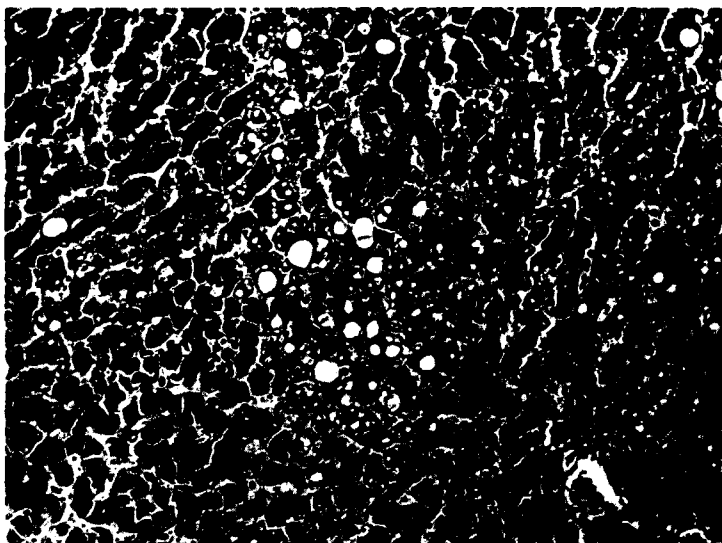
Fatality XI
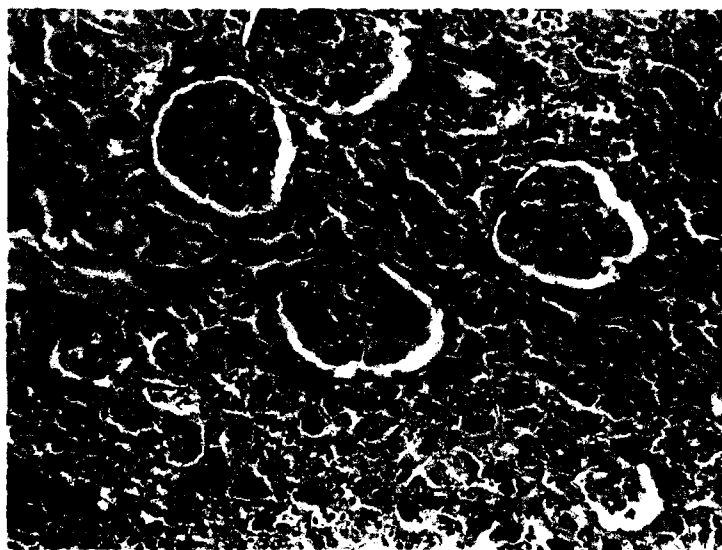

Fig. 8-11 (a) K.H., liver, H. & E. x 150.

Fig. 8-11 (b) K.H., kidney, H. & E. x 120.

Necropsy The only information available is that pulmonary oedema was present and 1100 ml pleural effusion.

In-Flight Cases

The following summaries are concerned with those fatalities following exposure to altitude in actual flight. For convenience the numbering will follow-on from the chamber cases, in chronological sequence.

Fatality XI K.H. 20 November 1950. UK. Time to death $10\frac{3}{4}$ hours. Reported by Sproull (1951); Haymaker (1957) case 8.

History A 29 year-old flight engineer, some 41 lb overweight, accustomed to flying at altitudes up to 30,000 feet. On the day of the fatal flight, a morning take-off was made in a large 4-engined transport specially equipped for meteorological research. He carried out his duties satisfactorily during a 2 hour 20 minute flight, 55 minutes of which was spent at 30,000 feet. On landing he complained of feeling shaky and he looked pale and cyanosed. He felt sick but was unable to vomit. He stated that he had experienced vague generalised abdominal pain during most of the flight. On examination his pulse was imperceptible and his blood pressure unrecordable. He was grossly cyanosed and mottled. Restless but rational. The circulatory collapse progressed relentlessly and he died $10\frac{3}{4}$ hours after first reaching 30,000 feet.

Treatment Raised foot of bed, warmth, glucose by mouth, oxygen, morphine gr. $\frac{1}{2}$ I.V., 5 mgm desoxycorticosterone acetate I.M., methedrine, nikethamide, pethidine.

Necropsy (36 hours after death).

Obese, cyanosed, mottled.

Lungs- Pleural effusions approx. 250 ml each side. Emphysematous and oedematous lungs.

Heart - 475 gm. Ventricles dilated. A 2.5 cm diameter endocardial haemorrhage on the ventricular septum.

Gut - Large petechial haemorrhages on the surface of the fatty mesentery.

Liver - Congested.

Kidneys - Normal.

Spleen - Normal.

Thyroid - Normal.

Adrenals - Normal.

Bone Marrow - Normal.

Brain - Congested. Pressure cone of left cerebellar hemisphere.

Histology (material kindly made available from RAF Institute of Pathology) (Fig. 8-11).

Lungs - Very congested, with moderate oedema in some areas.

Heart - No significant lesions.

Liver - Congested with marked fatty vacuolation. Some ceroid-like pigment.

Kidneys - Very congested and autolytic.

Skeletal muscle - Normal.

C.N.S. - (Report by Professor Blackwood. Sections made available for review).
No abnormality other than minimal neuronal change in frontal cortex. Full
examination of brain and cord revealed no lesions. One possible fat embolus
in one of several frozen sections of the brain.

Fatality XII "570889" 28 January 1953. USA. Time to death $11\frac{3}{4}$ hours.
Haymaker and Johnston (1955) case 11; Haymaker, Johnston and Downey (1956)
case 1; Haymaker (1957) case 11. AFIP Accession Number 570889.

History A 50 year-old passenger, approximately 60 lb overweight, occupied the
the rear of tandem seats in a jet trainer-type aircraft. Inefficient pressurisation
gave a cabin altitude of 35,500 feet for approximately one hour of the flight. The
victim complained of abdominal pain about 50 minutes after reaching altitude and
10 minutes later descent was commenced at 1,500 ft/min. The passenger was
observed to be slumped and was unresponsive to radio calls. On landing he was
found to be deeply unconscious and apnoeic, although respiration soon recommenced
when an airway was inserted. The pulse was feeble and the patient was comatose
and cyanosed. Lumbar puncture showed CSF at a pressure of 260 mm of water.
Circulatory collapse progressed and vomiting occurred frequently. Tremors and
jerking movements of the right leg were noticed. The patient died $11\frac{3}{4}$ hours after
the initial symptoms.

Treatment Oxygen and aminophylline i.v.

Necropsy (6 hours after death)

Deeply cyanosed in the upper half of the body. Obese.

Lungs - 100 ml pleural fluid. Left lung 650 gm. Right 725 gm. Congested and
oedematous.

Heart - 625 gm. Endocardial patches of congestion or haemorrhage on left vent-
ricle. Foramen ovale patent "admitting the tip of the little finger."

Gut - 750 ml. green fluid in stomach. Superficial mucosal ulcers.

Liver - 2900 gm.

Kidneys - 175 gm and 160 gm.

Spleen - 150 gm.

Brain - 1375 gm. Congested.

Vascular tree - Slight atheroma of left coronary artery and cerebral arteries.

Histology (Haymaker et al report and re-examination) (Fig. 8-12).

Lungs - Congestion and oedema.

Heart - Endocardial haemorrhage. Marked fragmentation of fibres. Slight scat-
tered fibrosis.

Liver - Congested and markedly fatty, distorting the normal architecture. Fat-
free vacuoles with inclusions reported.

Kidneys - Congested. Arteriolosclerotic changes. Marked autolysis of proximal
tubules, many tubular casts, 'haem' and hyaline. A single fat embolus re-
ported.

Fatality XII

Fig. 8-12 (a) 570889, liver, H. & E. x 185.

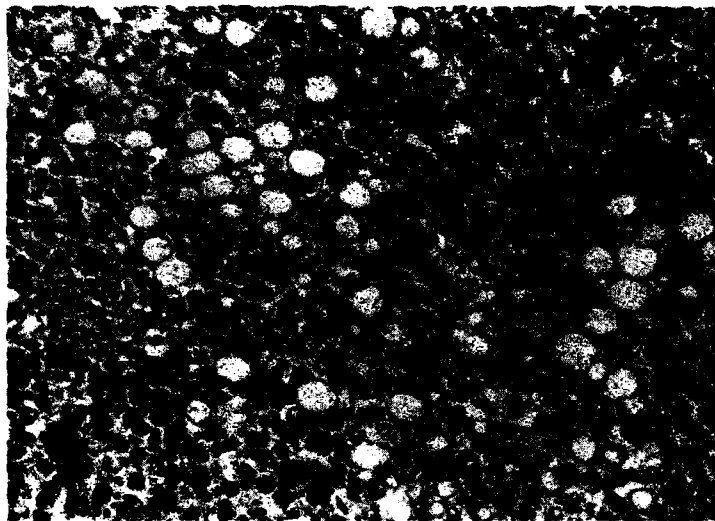Fig. 8-12 (b) 570889, kidney, H. & E. x 185.

Fatality XIII

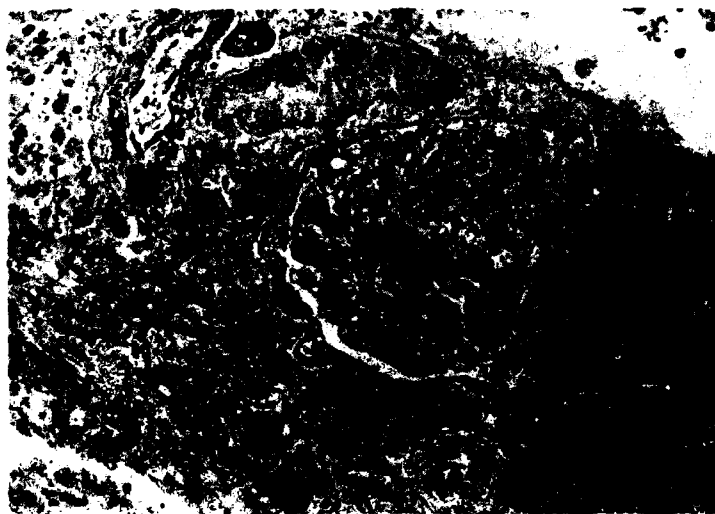Fig. 8-13(a) 638482, liver, H. & E. x 185.

Fig. 8-13(b) 638482, kidney, H. & E. x 185. Note space
left by dissolved-out fat embolus.

Adrenals - Some adipose tissue within the cortex.   Otherwise normal.

C.N.S. - Very marked scattered ischaemic wedge-shaped and geographical areas
of ischaemic damage and perivascular myelin rarefaction throughout the
brain.   (Haymaker, Johnston and Downey)

Fatality XIII   "638482"   19 March 1954.   USA.   Time to death $5\frac{1}{2}$ hours.
Anonymous Clinico-Pathological Conference (1955);   Haymaker and Johnston (1955)
case 12;   Haymaker, Johnston and Downey (1956) case 2;   Haymaker (1957) case
12.   AFIP Accession Number 638482.

History   A 34 year-old Army officer, grossly overweight by some 90 lb.   Pass-
enger in the rear of tandem seats in a jet trainer aircraft.   After 1 hour 20 minutes
at a cabin altitude of 26,000 ft the aircraft ascended to 39,500 feet, at which height
the cabin altitude reached 29,000 feet.   On attempting to level out the pilot noticed
interference with throttle movement.   Enquiry revealed that the passenger had
"numbness of the left side" and that he was cold.   Presumably he was clutching
the throttle control.   Descent was initiated within some $2\frac{1}{2}$ minutes.   The pass-
enger became completely incoherent and on landing he was found to be comatose,
but just rousable and 'livid red' in colour.   His left limbs were flaccid, the right
moved convulsively and were clonic.   His blood pressure was 180/120.   He was
admitted to hospital, where he was restless to a degree requiring restraint.
Lumbar puncture revealed no abnormality.   Circulatory collapse developed with
mottled cyanosis and after one right-sided convulsion the patient died.

Treatment   Oxygen, attempted stellate ganglion block (for possible cerebro-vas-
cular accident), 2.5 L 5% dextrose and added noradrenaline.

Necropsy   (1 hour after death)

The entire examination was carried out under water.   No gas bubbles were demon-
strated.

Lungs - Pleural cavities dry, lungs left 500 gm, right 500 gm oedematous.

Heart - 325 gm.   Subendocardial haemorrhages in left ventricle.   Moderate
atheroma of left coronary artery.

Patent foramen ovale, 4 mm x 1.5 mm not valvular.

Gut - Normal.

Liver - 1600 gm.

Pancreas - Fatty.

Kidneys - 130 gm and 150 gm.

Spleen - 150 gm.

Thymus - 5 gm, fatty.

Adrenals - 5 gm and 7 gm.

Brain - Congested.

Histology   (Haymaker, Johnston and Downey and review of material) (Fig. 8-13).

Lungs - Marked congestion and oedema.   Considerable fat embolism

Heart - Normal.

Liver - Severe fatty vacuolation congestion and possible early focal necrosis.

Kidneys - Very congested. "Autolysis" of proximal tubules. Haem casts reported. No fat emboli.

C.N.S. - Occasional fat emboli. Marked geographical ischaemic lesions scattered throughout the brain. Strange disruptive changes in the cervical cord are probably artefacts attributable to mechanical damage in removing the upper cord by traction from above. (Haymaker, Johnston and Downey)

Fatality XIV V.K. 9 November 1955. UK (W. German based). Time to death 15¼ hours. Fryer & Mason (1955); Fryer (1956); Mason (1962).

History This officer was a pilot, aged 38, of Central European origin. He had a long and distinguished flying history. Approximately 9 years before this occurrence he had been involved in an accident in which he had fractured his lumbar spine. The result had been some interference with control of his urinary bladder for which he found it necessary, on occasion, to wear a urine collection device. As a result of his sphincter dysfunction he had a mild bilateral hydronephrosis and hydroureter, with occasional ascending infections. He had another accident in 1949, in which his buttocks were burned.

He was somewhat overweight (approximately 44 lb by RAF standards). He was a non-smoker and non-drinker. His general health was good shortly before the incident. He slept poorly on the night of 8th November, being worried about an interview on the following day. He had a normal breakfast and at 10.40 a.m. he took-off from an airfield in Germany to fly an unpressurised training jet aircraft to England. In the front seat of this tandem-seat aircraft was a younger, less experienced co-pilot.

They climbed to 35,000 feet and after some 8 minutes V.K. was noticed to be breathing heavily and he complained of feeling unwell. He asked the co-pilot to take control and reduce altitude to 30,000 feet. At this height he felt better but he soon started to cough paroxysmally and then he appeared to lose consciousness. The descent was continued and the aircraft was landed at 11.45 a.m., having been some 12 to 15 minutes at or above 30,000 feet.

On examination, the pilot was found to be deeply unconscious and dusky in colour. His oxygen equipment was correctly connected and functioning. His eyes were moving from side-to-side; his reflexes were generally brisk but for the plantar and abdominal which were absent. His pulse was reasonable in rate and his blood pressure 130/100. Respiration was stertorous. Some 3½ hours later on admission to hospital his condition was little changed, although his blood pressure had fallen to 80/60 and his respiratory rate had risen to 30 per min. He remained cyanosed unless given oxygen. He was doubly incontinent. His blood showed a P.C.V. of 67%, a haemoglobin level of 128%, and 29,800 white cells per cu. mm. Lumbar puncture showed fluid at a pressure of 150 mm of fluid, with relatively normal composition. His temperature later rose to 103°F (rectal) and later 104.2°F, his coma fluctuated a little and he died of respiratory arrest at 02.20, some 15¼ hours after the initial symptoms.

Treatment Coramine I-M and I.V., oxygen approximately 600 ml dextrose-saline, aureomycin and penicillin.

Necropsy (12 hours after death).

Well covered and bull-necked, appeared older than declared age. Face and trunk cyanosed, with crops of what appeared to be petechiae over the anterior chest and shoulders. These in fact blanched under pressure from a glass slide.

Fatality XIV

Fig. 8-14 (a) V.K., liver, frozen section,
Fettrot 7B, x 55.
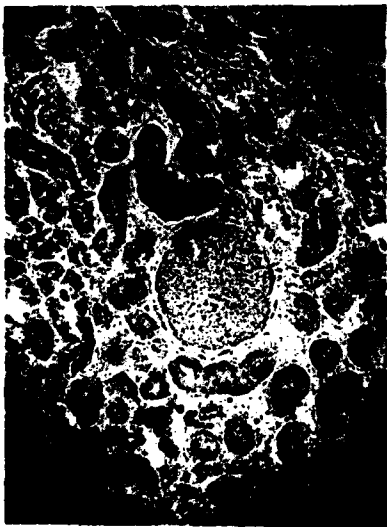
Fig. 8-14 (b) V.K., lung, frozen
section, Fettrot 7B, x 80

Fig. 8-14 (c) V.K., kidney, frozen
section, Fettrot 7B, x 80.

Fatality XIV

Fig. 8-15 (a)   V.K , myocardium, Iron haematoxylin & eosin, x 60.   Focal
myocarditis.

Fig. 8-15 (b) V.K., myocardium,
H. & E. x 270.   A necrotic focus.
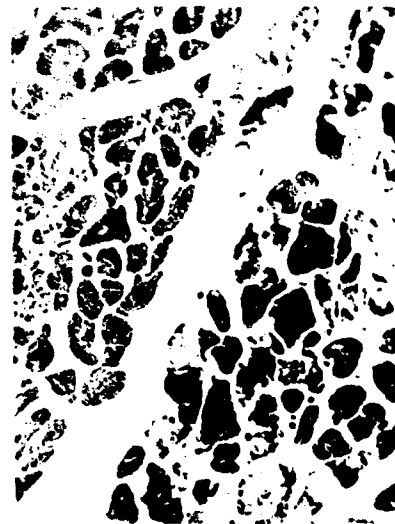
Fig. 8-15 (c) V.K., myocardium,
Heidenhain's Iron Haematoxylin x 445.
Loss of striations seen in transverse
section.

Fatality XIV

Fig. 8-16 (a) V.K., liver, Gomori Trichrome, x 40.

Fig. 8-16 (b) V.K., kidney, H. & E. x 165.

Lungs - 75 ml clear straw-coloured fluid in each pleural cavity. Lungs very
heavy, congested and partially collapsed at the bases. Frothy blood-stained
fluid extended into the bronchi and trachea.

Heart - Normal. Foramen ovale definitely fully closed.

Gut - Brownish fluid in the stomach. Haemorrhagic mucosa in segments of the
small intestine. Very heavy and fatty mesentery.

Liver - Congested.

Kidneys - Right smaller than left. Prominently filled radial vessels.

Spleen - Normal.
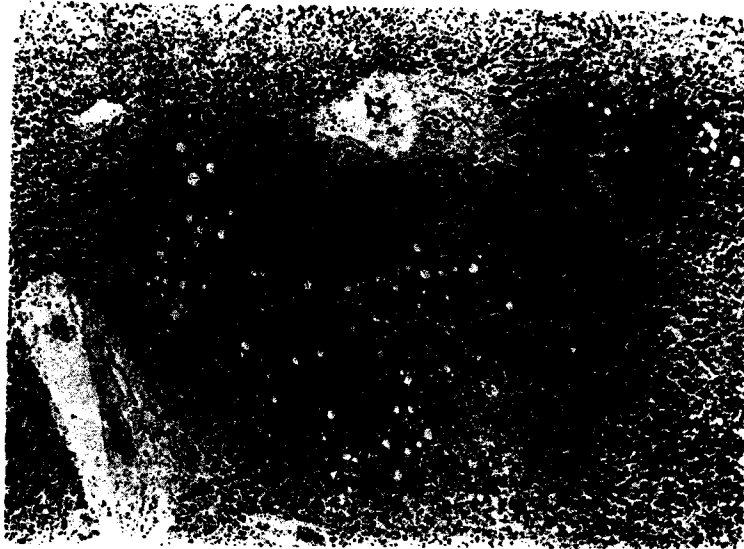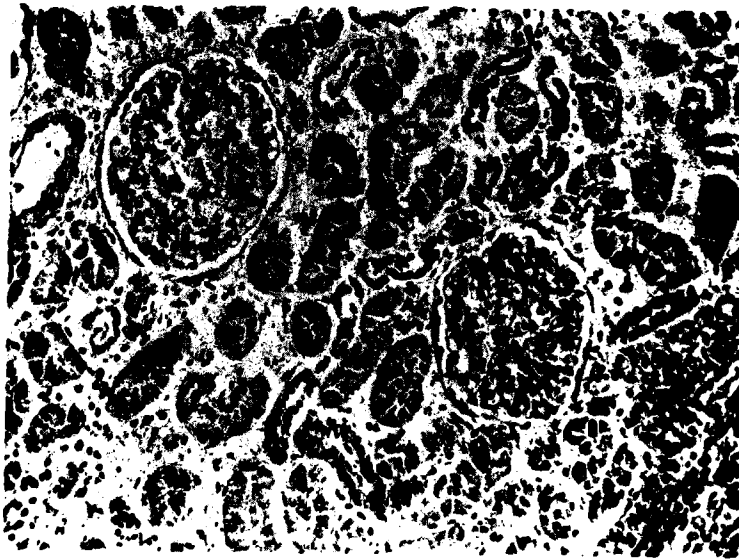
Thyroid - Normal.

Adrenals - Slight autolysis.

Brain - Somewhat congested. Bubbles in pial vessels, possibly introduced when
the calvarium was removed.

Spinal cord - Normal.

Histology   (own sections, plus report of Mason)   (Figs. 8-14, 8-15 and 8-16).

Lungs - Congestion and oedema. Some autolysis. Moderate numbers of fat
emboli (Fig. 8-14).

Heart - Slight brown atrophy and moderate fatty deposition within fibres. Slight
oedema. Focal leucocytic infiltration with loss of muscle fibre detail in
these areas (Fig. 8-15).. Fine fatty deposition within medial muscle fibres
of some coronary artery branches. No fat emboli.

Liver - Congested with marked fatty deposition of centrolobular distribution (Figs.
8-14 and 8-15).

Kidneys - A few fatty tubules. Congestion principally of the medulla. Very
striking loss of all histological detail in the tubules, to quote Mason (1962)
".... beyond what could be ascribed to post-mortem autolysis". Very few
glomerular fat emboli (Figs. 8-15 and 8-16).

Spleen - Congested. Very occasional fat emboli.

C.N.S. - Rather sudanophilic material within many vessels but no real fat emboli.
Many fat-laden macrophages (lipophages) in the Virchow-Robin space. One
tiny perivascular haemorrhage around a single vessel in one section. No
ischaemic or degenerative lesions seen anywhere in brain or cord.

**Fatality XV   K.Y.   6 April 1956.   UK   (Cyprus-based).   Time to death 11½
hours.   Mason (1956);   Fryer (1956);   Mason (1962)**

History   This officer, aged 34, was ex-aircrew, but not in current flying status.
He was a passenger in a jet trainer aircraft of the same type as that involved in
fatality case XIV. The flight commenced at 08.30 and the machine climbed to
30,000 feet in 10 minutes. Forty minutes after reaching height the pilot noted that
his passenger did not reply to calls on the intercommunication system and he was
seen to be slumped in his seat. A descent was made to 20,000 feet and then after
some 30 minutes, continued, until the aircraft landed at 10.00 hours.

The victim was deeply unconscious, making convulsive movements of the left arm
and wailing continuously. His condition on reaching hospital some 30 minutes

later was deep coma, cyanosed,with mottling of the trunk. He was spastic but
for the left arm, and his right facial muscles were paralysed. His plantar reflexes
were extensor. One hour later his blood pressure was 80/0 and his haemoglobin
concentration 145%. Lumbar puncture revealed no abnormality. He developed
pulmonary oedema and became pyrexial. At 14.30 his PCV was 70%. A
catheter specimen of urine showed heavy albuminuria. He died 11¼ hours after
his loss of consciousness.

Treatment   Oxygen, paraldehyde, intra-muscular cortisone, eucortone, norad-
renaline; saline, dextrose and 1/6 M lactate to a total of approximately 4 litres.

Necropsy   (approximately 38 hours after death).

Stoutly built, bull-necked, apparently older than declared age, mottled above the
clavicles.

Lungs - 500 ml clear fluid in each pleural cavity.   Left lung 750 gm; right 650 gm,
     oedematous.

Heart - 40 ml pericardial effusion.   Heart 400 gm.   Right side dilated.   Foramen
     ovale patent with a well-developed flap overlying the patency; would stretch
     to 1 cm diameter (Fig. 8-17).

Gut - Multiple tiny haemorrhages over abdominal viscera.

Liver - Large and pale, 1850 gm.

Kidneys - Slight pitted scarring with moderate right hydronephrosis.

Spleen - 100 gm.

Thymus - Enlarged.

Adrenals - Normal.

Brain - Congested and oedematous, 1420 gm.

Spinal cord - Congested.

Histology   (own preparations plus report of Mason)   (Figs. 8-18 and 8-19).

Lungs - Congestion and oedema.   Moderate fat embolism, (Fig. 8-18).

Heart - Oedema and diffuse fine fibrosis (diagnosed by Mason as compatible with
     inactive past rheumatic disease).   One fat embolus.

Liver - Congested with widely distributed fatty change, (Fig. 8-19).

Kidneys - Considerable scarring, with a few casts.   Congestion of medulla.
     Blood failed to stain in glomeruli.   Marked tubular change, even allowing for
     delay in necropsy.   Several glomerular fat emboli and some fat in larger art-
     eries, (Figs. 8-18 and 8-19).

C.N.S. - Extensive and careful examination failed to reveal any lesions other than
     a rather large number of perivascular lipophages.   A haemorrhagic cord
     lesion has been ascribed by Mason, the prosector, to handling damage.   No
     unequivocal fat emboli.

Fatality XVI   L.L.C.   14 October 1957.   USA (Japan based).   Time to death
12¾ hours.   Odland (1959); Robie, Lovell and Townsend (1960) case 1.   AFIP
Accession Number 851551.

Fatality XV
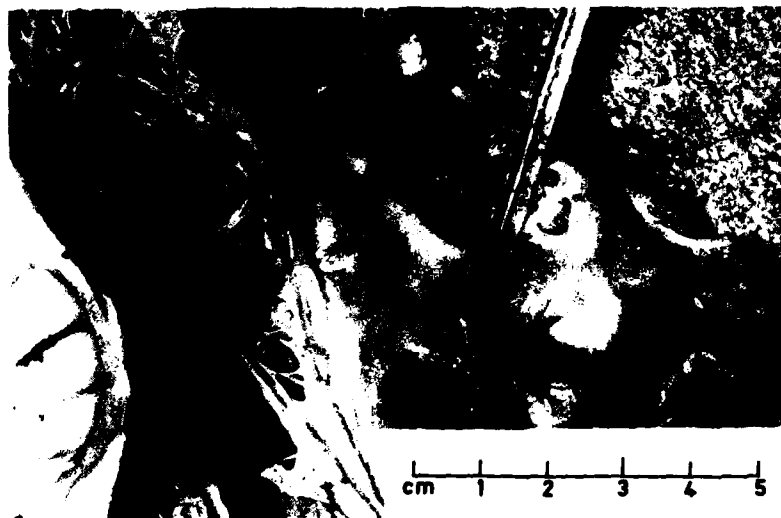
Fig. 8-17   K.Y., heart (fixed).   Probe through patent foramen ovale, seen from left (above) and right (below).

Fatality XV
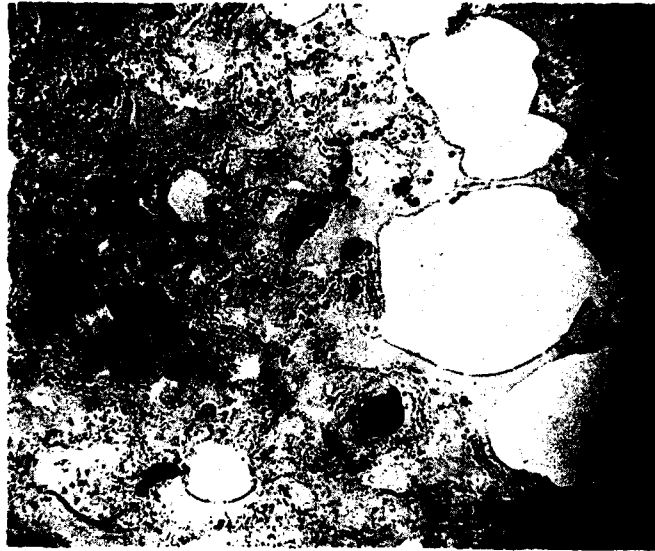
Fig. 8-18 (a) K.Y., lung, frozen section, Fettrot 7B, x 80.
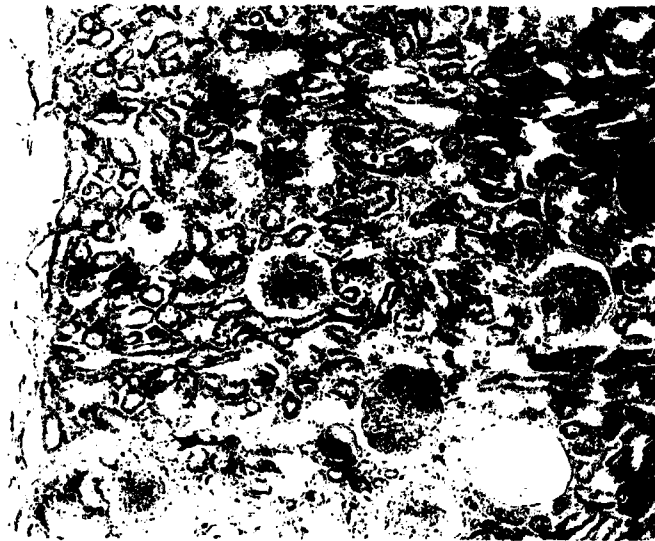
Fig. 8-18 (b) K.Y., kidney, frozen section, Fettrot 7B, x 50.

Fatality XV
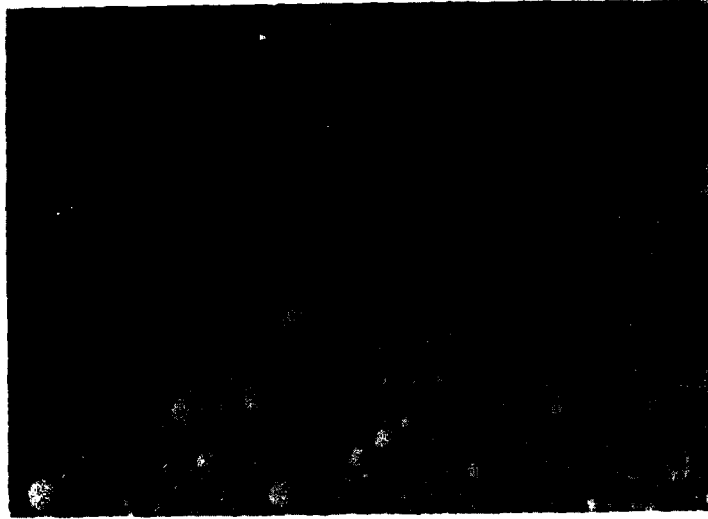
Fig. 8-19 (a) K.Y., liver, H. & E. x 130
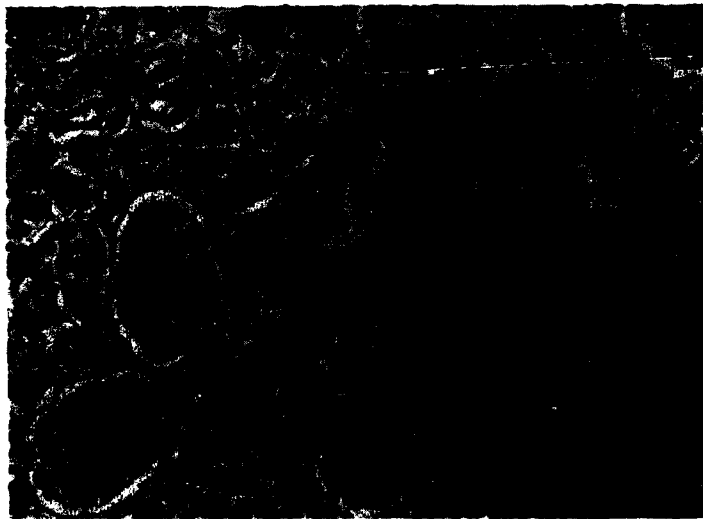
Fig. 8-19 (b) K.Y,, kidney, H. & E. x 130.

Fatality XVI

Fig. 8-20 (a) L.L.C., liver, H. & E. x 130.
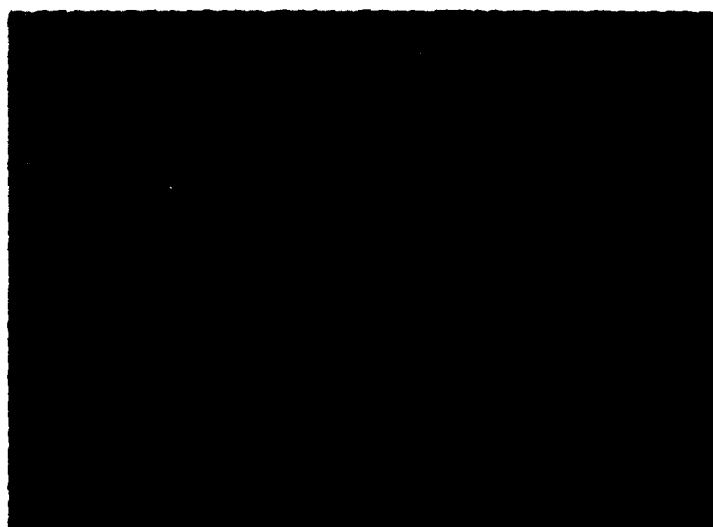
Fig. 8-20 (b) L.L.C., kidney, H. & E. x 130. Note dilated afferent
arterioles.

History (some details culled from a copy of protocols kindly furnished by Colonel Townsend).

This man was a very experienced pilot, aged 36, approximately 65 lb overweight. He was taking butazolidine for "incipient gout" at the time of his fatal flight. He and a radar-observer/navigator took off in a tandem seat jet aircraft at 21.36 hours and climbed to an altitude at which the interior of the pressure cabin was at a pressure equivalent to 22,000 feet. The pilot, who was uncomfortably seated in the cockpit owing to limited head-room, complained of feeling sick after about 6 minutes at altitude and 7 minutes later he complained of chest cramps and coughed. (Accounts vary, some put the time of this incident at 30 minutes after take-off). The radar observer took control as the pilot appeared to be unconscious, with stertorous respiration; in spite of lack of pilot training he managed to make a reasonable crash-landing on the airfield 1 hour 39 minutes after take-off. The patient was moribund and although he could at one stage be made to respond vaguely to stimuli including speech, he was never rational. He was cyanosed and sweating. His pulse was 84/min. and B.P. 90/60. Deep reflexes were absent. His ECG showed evidence of right heart strain. In spite of vigorous treatment he developed circulatory collapse, fever to 102°F, periodic respiration and died 12¾ hours after the onset of symptoms in the air.

Treatment Oxygen, caffeine, levarterenol, antibiotics and 'cedilanid'. Unstated quantity of saline by intravenous route.

Necropsy (21½ hours after death).

Cyanosed, very obese, looking considerably older than his stated age.

Lungs - Pleural effusions 300 ml left; 150 ml right. Lungs heavy, dark and moist, left 850 gm; right 800 gm.

Heart - 20 ml pericardial effusions. No bubbles on opening the heart under water. Heart weight 460 gm. Flap-guarded patency of the foramen ovale.

Gut - Very fatty mesentery.

Liver - Large and pale. 2800 gm.

Kidneys - Moderate left hydronephrosis. Left kidney 160 gm, right 175 gm.

Spleen - Slightly enlarged, 350 gm.

Brain - Weight 1800 gm. Moderate cerebellar pressure cone.

Histology (reports and own sections) (Fig. 8-20)

Lungs - Very marked congestion and oedema. Very marked submucosal congestion of the trachea. Minimal fat embolism reported by Robie et al, more extensive by Odland.

Heart - Not reported on by Odland. Some focal 'tinctorial' changes with focal increase in interstitial cells reported by Robie et al. Blocks examined by the writer showed possible focal areas of very early degeneration. Slight coronary atheroma.

Liver - Very marked centrolobular fatty change and a few foci of polymorphonuclear leucocytes.

Kidneys - Very congested with distension of afferent arterioles. A few casts. Marked tubular autolysis or necrosis. A few glomerular fat emboli reported by Robie et al and by Odland.

C.N.S. - Focal and geographical ischaemic lesions were detected by Robie et al

with myelin stains, but were apparently missed in the earlier report by Odland. The spinal cord was poorly preserved. It showed no specific lesions.

Fatality XVII J. A. C. 26 November 1958. USA. Time to death 9 hours.
Robie, Lovell and Townsend (1959) case 2. AFIP Accession Number 909803.

History (from Robie et al and protocols kindly supplied by Colonel Townsend).

This 32 year-old Petty Officer, who was very overweight (99 lb above his age/height average in RAF tables) was a crew member in a jet medium bomber/reconnaissance aircraft, the cabin pressurisation of which was not functioning. After some 90 minutes at 33,000 feet he felt pain in the left knee and soon thereafter he had lower and mid-abdominal pain and nausea, and he felt weak and breathless. After landing he felt extremely weak and almost collapsed. He was breathless and his supra-pubic pain persisted. He was pale, somewhat cyanosed and sweaty.

He was admitted to hospital some 5 hours later: histories in the published account and the original prosector's notes differ considerably, but he clearly had no localising neurological signs except for facial weakness bilaterally. There was pronounced tachycardia and he developed pulmonary oedema. He was hypotensive and terminally had a left-sided focal motor seizure. He died of ventricular fibrillation some 9 hours after his first symptoms.

Treatment Aramine, O_2 (under pressure), 1 litre of 5% Dextrose, levophed, atropine, papaverine, aminophylline, cedilanid, 100 mgm hydrocortisone I.V., 100 mgm Cortef.

Necropsy ($14\frac{1}{2}$ hours after death)

Very obese, cyanosed, looking older than his true age. Incision for open cardiac massage.

Lungs - 600 ml clear fluid in right pleural cavity. Lungs mottled, congested and oedematous. 1360 gm together.

Heart - 420 gm. Dilated with a few petechiae and some discolouration. (possibly associated with cardiac massage). Very detailed post-mortem notes made no mention of septal defect and the atrial septum can safely be assumed to have been closed (the protocol even included measurements of all valve ring diameters and heavily annotated diagrams but no comment against the relevant area in the illustrations). No bubbles were seen in the heart or great vessels.

Gut - Normal.

Liver - Pale, fatty with patchy congestion. 1520 gm.

Kidneys - Left 135 gm; right 125 gm. Congested.

Spleen - 160 gm.

Thyroid - 40 gm.

Adrenals - Described as small and flabby. 13 gm.

Bone Marrow - Sternum, spine and ribs opened and found normal.

Brain - Congested. 1500 gm.

Histology (from Robie et al's report, protocols and own sections) (Fig. 8-21).

Lungs - Congested and oedematous. Considerable autolysis. No fat emboli.

Heart - Congested.

Liver - Congested with mid-zonal fatty change (described as minimal by Robie et al but quite marked in their illustration).

Kidneys - Congested and advanced autolytic changes. No fat embolism according to Robie et al, although minimal embolism reported in protocol.

Thyroid - Congested.

Adrenals - Autolytic.

C.N.S. - Congestion and oedema. No ischaemic lesions or fat emboli.

Debatable and Dubious Cases

In addition to the cases enumerated above, there are various reports of deaths in circumstances where the process underlying decompression sickness may have arisen.

One example is Case 3 of Robie, Lovell and Townsend (1954). This was a 40 year old pilot who, at a cabin altitude of 20,000 feet complained of pain in his shoulders, visual symptoms and dizziness. He apparently discovered a faulty connection in his oxygen equipment. Within a few minutes he stopped breathing and he was pronounced dead when the aircraft landed 24 minutes after the onset. The pathological findings included gross pulmonary emphysema, congestion of the lungs and cerebral oedema. The liver was fatty. All viscera were the site of intense congestion. There was no fat embolism.

This case is remarkable for the almost immediate death and the absence of pulmonary oedema. It is tempting to ascribe the case to hypoxia complicated by bends, hypoxia being a recognised predisposing factor. Strangely the oxygen connections were apparently all intact, so it must be presumed that the pilot reconnected his supply hose before losing consciousness.

The writer's opinion is that this was a case of hypoxia and bends, followed by syncope and respiratory arrest due to cerebral circulatory insufficiency during forced maintenance of the sitting position (see Chapter 9).

Deaths in the decompression chamber are extremely rare, although it is recorded that an American chamber operator committed suicide by removing his mask whilst alone at altitude (Haymaker and Johnston, 1955, case 15). Cerebral changes were described, the authors noting the strange feature of scattered foci of ischaemic change affecting myelin stains in spite of the certainly very brief period between onset of hypoxia and death.

Two somewhat bizarre deaths were reported from Germany by Pioch (1960) and by Henn (1962). Two men, aged 21 and 26, entered a decompression chamber without authority (it is believed that they were installation engineers), with the pumps running. They closed the door and consequently ascent commenced. They donned oxygen masks. Ten to twenty minutes later they were observed, lifeless, on the chamber floor; a window was smashed and descent was almost immediate. The peak altitude was not noted, but later calculations suggested that they reached 46,000 to 55,000 feet. Their masks were still in place. They did not respond to resuscitation attempts.
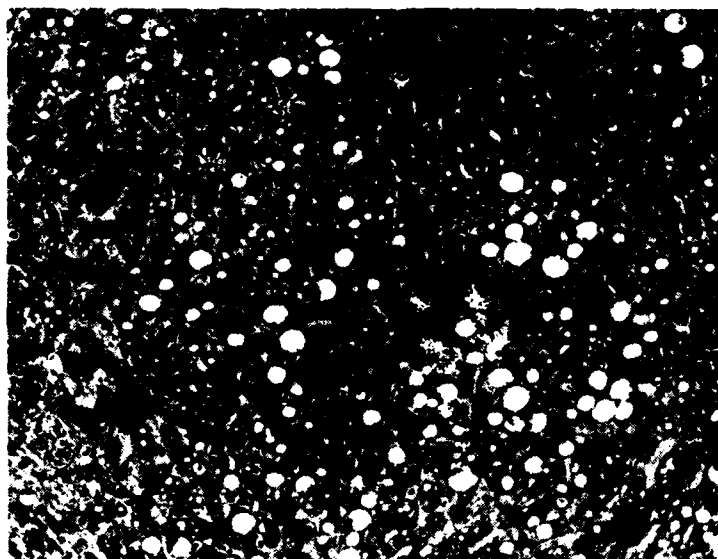
Fatality XVII

Fig. 8-21 (a) J.A.C., liver. (From Figure 7 of Robie, Lovell and Townsend), reproduced by courtesy of the Aerospace Medical Association.

Fig. 8-21 (b) J.A.C., kidney, H. & E. x 130.

Fig. 8-21 (c) J.A.C., heart, H. & E. x 130, showing focal necrotic change without inflammation.

The post mortem findings were described as scattered petechiae, general visceral congestion and fat embolism of the brain and heart (Pioch, 1960). Much was made of apparent gas bubbles within fat emboli and so-called 'classical' fat-free vacuoles in heart fibres and liver cells. Henn (1962) made much of the cerebral fat emboli and bubble-like spaces and also described dilated perivascular spaces with many lipophages.

The writer was most fortunate in that, having heard of these deaths, contact was established with the prosector, Professor Elbel, and wet specimens of all tissues except the brain were most generously given for examination. The findings are somewhat at variance with those published and must be recorded here.

The first case showed intense pulmonary congestion and some haemorrhage and oedema. The heart showed marked vacuolation at the nuclear poles of muscle fibres. The liver was intensely congested with a few scattered fatty cells, with vacuoles lined with lipofuscins and a few apparently watery vacuoles. The other tissues were near-normal. Frozen sections showed some fatty droplets in some alveolar phagocytes but no fat embolism. The claimed fat embolism in the heart was not confirmed. The liver showed generalised extremely fine fatty deposits in parenchymal cells. Kidney tissue was not available.

The second case showed in the lungs minimal pulmonary oedema, massive congestion and haemorrhage. The heart revealed many vacuoles in myocardial fibres and the kidneys gross autolysis. The liver was almost fat free but contained a few watery vacuoles. Fat embolism of myocardium was again not confirmed, but one embolus was seen in many kidneys sections and two in a thick section of lung.

Pioch and Henn make much of the fatty emboli which, in the writer's preparations, were remarkably sparse. The lungs were not mentioned by Pioch. The almost complete absence of fatty emboli in the pulmonary bed must surely exclude the classical type of fat embolism pathology so avidly pursued by the German authors. Henn's lengthy speculations about extremely rapid (10 minute) or post-mortem passage of fat through cerebro-vascular endothelium and uptake by lipophages becomes much less realistic in the light of the negative findings in the lungs. It is undeniably difficult to differentiate between extravascular and intravascular droplets in the commonly found non-specific perivascular lipophage-containing brain.

Certainly the writer finds it impossible to reconcile the straight-forward hypoxic type of changes in viscera as described by Pioch and confirmed in his own preparations with the speculations by Henn on the question of cerebro-vascular embolism.

Finally, there remains a further group of poorly documented cases, about which one feels hesitant to write. Rascher, in Germany in 1942, carried out a series of experiments on concentration camp inmates, some records of which remain in captured documents submitted to the War Crimes Tribunal and of which a brief summary is included in a book by Mitscherlich and Mielke (1949).

Victims, each suspended in a parachute harness, were decompressed to altitudes in excess of 50,000 feet and then brought down at speeds representing parachuting velocities. Many died and others were killed. The picture was clearly complicated by hypoxia, but from the scant reports and few photographs it would seem that cerebro-vascular and intracardiac bubbles were seen. Cardiac tamponade was also recorded.

Analysis of findings

It is convenient and indeed necessary, at this point, to attempt an overall survey of fatalities. Because of reservations already expressed about the cases of Pioch, Rascher and Case 3 of Robie et al, the review will be limited to the seventeen cases summarised earlier in this chapter. Discussion will be deferred, on the whole, until Chapter 9.

Table 8-2 displays the basic data on the victims and Table 8-3 the clinical features of their terminal illness.

Table 8-4 lists a number of the more common abnormal necropsy findings. Where blanks are left the data were either not taken or not recorded.

The main histological features are shown in Table 8-5.

Summary

The major discussion on the findings in fatalities will be reserved for Chapter 9. However, it is useful to summarise a number of points which clearly emerge from consideration of the data in this and preceding chapters.

Severe and fatal cases are rare. The large majority experience severe symptoms at altitude although a few have predominantly lower abdominal pain and nausea. There appear to have been no fatalities following an uneventful sojourn at altitude, uncomplicated skin irritation or bends. In no case has there been evidence of hypoxia during the flight.

Descent generally leads to partial recovery, although in all five cases in tandem seat jet aircraft no such lucid interval occurred. Deterioration, when it occurs is rarely delayed beyond two hours and very rarely indeed beyond four hours.

Clinically deterioration is almost always accompanied by haemoconcentration, polymorph leucocytosis and fever. Peripheral vascular collapse and cyanosis are common, but hypotension is generally a late complication, as is pulmonary oedema. Neurological signs are variable and often slight.

Death is rarely delayed more than eighteen hours. In no case uncomplicated by hypoxia has death been recorded in less than five and a quarter hours.

Those affected are commonly over thirty and almost invariably overweight. Many have been remarked upon being of stocky build with bull-neck, barrel chest and apparently prematurely aged.

Effusions into serous cavities almost always occur, as does an accumulation of oedema fluid within congested lungs. Fatty change in the liver is remarkably uniformly found, as is what may be termed accelerated renal tubular autolysis. Fat emboli are often present in small numbers in the lungs and less commonly in systemic vascular beds. Gas bubbles have not been seen with certainty.

Patency of the foramen ovale is common, but not universal.

Cerebral ischaemic changes are sometimes marked, occasionally minimal and frequently completely absent. Spinal cord lesions are quite exceptional.

Other lesions observed include focal myocarditis, renal afferent arteriolar dilatation and early focal hepatic necrosis.

Table 8-2   Fatalities : build and flight data

Number	Age	Height (in.)	Weight (lb)	Overweight* (lb)	Peak altitude (ft)/Time (min)
I	25	–	–	+	38,000/72
II	26	72	184	23	38,000/35
III	22	70	180	29	38,000/85
IV	38	–	200 or 220?	++	30,000/60 & 38,000/sec.
V	28	–	–	+(?)	37,000/120
VI	22	68	162	18	30,000/19
VII	23	70	180	28	30,000/23
VIII	33	70½	181	22	40,000/8
IX	37	64	161	29	25,000/25 & 40,000/1-2
X	28	–	–	'Average'	35,000/120
(XI	29	69½	194	41	30,000/55
(XII	50	72	240	60	35,500/60
(XIII	34	71	250	89	26,000/80 & 29,000/2½
(XIV	38	67½	191	44	35,000/8 & 30,000/4-7
(XV	34	65	165	28	30,000/40
(XVI	36	73	235	65	22,000/22
(XVII	32	65	235	99	33,000/approx. 120

(* from tables of Morant, 1946)

Table 8-3   Fatalities : clinical data

Number	Bends	Symptoms at Altitude			Collapse
		Chokes	CNS	Abdomen	
I		+			Imp.
II	+		?	+	Imp.
III			+		Imp.
IV	+	+	+		Imp.
V					Imp.
VI		+	+		+
VII		+			+
VIII	+		+		Imp.
IX		+			+
X	+	?			
(XI				+	Imp.
(XII				+	+
(XIII			+		+
(XIV		+			+
(XV					+
(XVI		+		+	+
(XVII	+			+	Imp.

(Imp. = impending)

Number	Lucid Interval (hr)	PCV	Temp. (°F)	White cells (thou/mm^3)	Time to death (hr)
I	1-1½	-	-	-	8½
II	Brief	65	108.4	20.2	71
III	Approx. 1-6	-	103	-	16¾
IV	1	60	-	23	17¼
V	¼	-	-	-	13-14
VI	Partial 1-2	55	106.2	29.85	38½
VII	Brief	57	107.6	20	55½
VIII	Nil	Normal	105	10.8	45
IX	½	69	-	17	5¼
X	2¼	-	-	-	17
(XI	? Brief	-	96	-	10¾
(XII	Nil	-	-	-	11¾
(XIII	Nil	-	-	-	5¼
(XIV	Nil	67	104.2	29.8	15¼
(XV	Nil	70	99.8	-	11¼
(XVI	Nil	-	102	-	12¼
(XVII	? 3-4	-	-	-	9

Flight

Table 8-4   Fatalities : Necropsy data

Number	Pleural Effusion (L)	Lung Weight (gm)	Pericard. Effusion (ml)
Normal Value	0	700-1000	0
I	1.3	907	150
II	0	-	30
III	1.2	-	5
IV	1.5	1592	10
V	1.8	-	15-20
VI	0	1700	75
VII	0.06	1786	20
VIII	0.3(contam?)	1000	35
IX	0.72	1010	0
X	1.1	-	-
(XI	0.5	-	-
(XII	0.1	1375	-
(XIII	0	1000	-
(XIV	0.15	-	-
(XV	1.0	1400	40
(XVI	0.35	1650	20
(XVII	0.6	1360	20

(Flight, left margin)

Number	Foramen ovale	Liver Weight (gm)	Brain (gm)	Heart Weight (gm)
Normal Value		1500-1800	1215-1400	300-400
I		1635	-	350
II	-	-	-	-
III	-	-	-	-
IV	-	2395	-	410
V	? closed	-	-	-
VI	-	1700	-	350
VII	-	1673	1425	397
VIII	? closed	1950	-	-
IX	Pat.	1340	-	320
X	-	-	-	-
(XI	-	-	-	475
(XII	Pat.	2900	-	625
(XIII	Pat.	1600	-	325
(XIV	closed	-	-	-
(XV	Pat.	1850	1420	400
(XVI	Pat.	2800	1800	460
(XVII	closed	1520	1500	420

(Flight, left margin)

Table 8-5   Fatalities - Histological Data

Fatality No.	Lung			Heart			Liver	
	Congestion	Oedema	Fat Emb.	Myocarditis	Fat Emb.	Congestion	Necrotic foci	Fatty change
I	+	++	±	0	-	+	0	++
II	++	++	±	0	-	++	0	+
III	++	++	+	0	-	++	0	++
IV	0	0	0	0	-	+	0	++
V	++	++	-	±		+		++
VI	-	-	-	±	-	-	-	-
VII	+	++	+	0	0	+	0	++
VIII	+	+	0	0	-	++	+	++
IX	+	+	+	0	-	++	0	++
X	-	-	-	-	-	-	-	-
XI	++	+	-	0	-	+	0	++
XII	+	+	0	0	-	+	0	++
XIII	++	++	++	0	0	++	?	++
XIV	++	++	++	++	0	+	0	+++
XV	++	++	++	0	±	+	0	+++
XVI	++	++	±	+	-	+	+	+++
XVII	++	+	0	0	-	+	0	++

Fatality No.	Kidney		Afferent dilatation	Brain		Spinal Cord	
	'Autolysis	Congestion		Fat Emb.	Ischaemic foci	Fat Emb.	Haemorrhages
I	++	++	0	-	±	0	-
II	++	+	0	0	±	0	-
III	++	+++	-	-	±	0	-
IV	++	++	0	-	±	±	++
V	++	+++	++	-	0	-	0
VI	-	-	-	-	-	-	-
VII	±	+	0	0	0	0	-
VIII	±	+	0	?	+++	±	-
IX	++	+	0	-	0	0	0
X	-	-	-	-	-	-	-
XI	++	++	0	-	0	?	0
XII	++	+	0	±	+++	±	-
XIII	++	++	0	0	+++	0	?
XIV	++	+	0	+	0	0	0
XV	++	++	0	++	0	0	?
XVI	++	++	+	+	++	0	0
XVII	++	++	0	±	0	0	-

Key

0   indicates absent
-   indicates not known
±   indicates equivocal

9

The Aetiology and Mechanism of Post-Descent Shock

Introduction

We have considered severe and fatal cases in the preceding chapter and have in particular summarised the pathological findings. It now remains to make an attempt to characterise the factors and findings with the aim of ascertaining causes, separating effects and delineating preventive measures.

To these ends many have striven, with conspicuous lack of success or with success limited to a minority of readers.

General reviews have been appended to most case reports; particularly the reader is referred to Haymaker and Davison (1950), Sproull (1951), Haymaker and Johnston (1955), Haymaker, Johnston and Downey (1956), Haymaker (1957), Mason (1962) and two papers by Fryer (1962 and 1962a).

What are the questions we need to ask ourselves? It is suggested that there are three relevant enquiries to be pursued in the analysis of severe and fatal post-descent shock. They may be conveniently referred to as Who, Why and How?

Who? What are the characteristics, if any, which lead to susceptibility so slight as that calculated by Adler (1950); serious collapse occurring in 0.015% of those exposed and death in 0.0007%?

Why? What are the particular features of flights, real and simulated, which give rise to severe post-descent phenomena?

How? What are the physiological and pathological processes involved in the post-descent syndrome or syndromes.

Who are the Susceptible Few?

Table 8-1 lists the characteristics of those known to have died from subatmospheric decompression sickness. As has already been noted many were aged 30 or more and almost all were overweight. A few had underlying disease; two renal, one brucellosis and one gout. However, it cannot be ignored that they were almost all of current aircrew medical standard, at least one was a non-smoker and total abstainer, each judged himself and was judged by his colleagues as fit on the day of the incident and many were examined medically on that day (the decompression chamber cases). Quite frankly, no aviation medicine practitioner would have foreseen disaster if given all that could possibly be discovered about those men, with the possible exception of those four cases 60 lb or more overweight.

Why did a particular ascent prove fatal, or nearly so?

Again, examination of Table 8-1 reveals no particular pattern of ascent. Only one case involved a rapid decompression (case IX, $4\frac{1}{2}$ sec. from 25,000 feet to 40,000 feet), few were prolonged and, indeed, some were such as to be regarded on all evidence elsewhere in this thesis as most unlikely to result in any form of decompression sickness. For example, case XVI's flight of twenty-two minutes at 22,000 feet, cases VI's and VII's under twenty-five minute exposure to 30,000 feet and case VIII's mere eight minutes at 40,000 feet. In every case the oxygen equipment was subject to careful scrutiny and found fully functional. No particular exertion was undertaken, no fumes encountered, no exceptional physical or mental stress imposed. Strangest of all, in at least three cases, (the in-flight incidents affecting cases XI, XIV and XVI) men were undertaking what would appear to be routine flights in no way different from their normal daily duties, in aircraft with which they were fully familiar and in which, to the best of our knowledge, they had never before experienced any form of decompression sickness.

How does the syndrome develop and why does it prove fatal?

After the preceding, unrewarding enquiries, it was to be hoped that at necropsy would be found the answer; some anomaly or concealed disorder which singles out an individual on a particular occasion. Sadly, no such answer emerges, although many authors have pursued their own theories, some with much more enthusiasm than would seem warranted. Discussion on this topic comprises the bulk of this chapter. To anticipate much of that, it seems that some process, accompanied by signs and symptoms other than simple limb pain, is initiated at altitude and this generally gives rise to some degree of general malaise or pre-syncope. Descent relieves the primary symptoms, except in a group of in-flight cases (cases XII to XVI), but within four hours deterioration becomes manifest. Severe illness ensues, almost always with haemoconcentration, fever and leucocytosis; circulatory failure becomes evident as pulmonary oedema develops, effusions accumulate, cyanosis intensifies and, often after considerable delay, the blood pressure falls.

At necropsy various conditions have been discovered which could perhaps intensify susceptibility; patency of the foramen ovale, fatty liver and multiple cerebral ischaemic foci (Table 8-3). However, none appears to be an essential feature. Indeed, no common thread seems to exist which links the victims of fatal decompression sickness, either by way of antecedent anomaly or pathological process.

In an attempt to formulate a unifying theory of causation, many theories have been advanced regarding the mechanism underlying the pathological findings. To review these theories inevitably involves a critical examination of our knowledge of the mechanisms and pathology of shock. In an effort to provide such a review and to advance the writer's own ideas the remainder of this chapter is devoted to a consideration of the physiological, pathological and experimental evidence, under the following headings:

The Pathological Picture - a brief resume of Chapter 8.

The Pathology of Shock - with particular reference to hepatic and renal changes.

Specific theories concerning fatal altitude decompression sickness:

Gaseous Embolism: cerebral
generalised
via pulmonary capillaries
via pulmonary shunts
via the vertebral plexus
via the foramen ovale

Autochthonous Bubbles

Fat Embolism: from adipose tissue
from bone marrow
from fatty liver

Toxaemia and Bacteraemia

Endocrine Defect

Trapped Gas Barotrauma

The Pathological Picture

The general picture, if indeed there is one, in the decompression fatality is one of visceral congestion, pulmonary oedema, effusions, fatty liver, renal tubular change, pyrexia, leucocytosis and haemoconcentration. What is the sequence of events and how many of the structural changes are sequelae, one of another?

Haemoconcentration is in almost all cases early. For example, fatal case III (C.S.) developed a PCV of 65% within one hour of his initial symptoms at altitude, Cotes (1953). Fever would appear to develop later, as does the rise in white cell count.

Decrease in the circulating volume without loss of cellular content must lead to a great increase in blood viscosity. This may perhaps underly the intense peripheral vaso-constriction and peripheral pallor and cyanotic tinge.

Pulmonary oedema as a clinical event would seem to be a late event in almost all cases, as also in hypotension. It would therefore seem likely that the failure to maintain an effective circulation is secondary to the peripheral changes rather than central (cardiac) in origin.

The question which remains is whether the other lesions, particularly those in the liver and kidney, are the result of the haemodynamic changes, independently produced or antecedent to the fatal illness.

The Pathology of Shock

The general pathology of shock is but poorly characterised, not surprisingly since so many methods have been used to produce shock experimentally and clinical fatalities are so often associated with multifarious causes and modes of treatment.

Moon (1948) made a particular study of secondary shock, using material from the U.S. Armed Forces Institute of Pathology (AFIP). He looked for changes common to death in a state of shock, whether it resulted from trauma, burns, poisoning, infection, anoxia, decompression (he used fatal cases II and IV,) heat stroke or abdominal emergencies. His main findings were pulmonary congestion and oedema.

Effusions were sometimes seen, particularly in burn shock, renal tubular necrosis, parenchymatous degeneration of the liver and, occasionally, focal degeneration within the adrenal glands.

He described faithfully the findings in the two altitude deaths, attributing the tissue changes to the shock rather than vice-versa.

Mallory (1949) reached very similar general conclusions about the tissue changes arising during death in a shocked condition. Davis (1949) made the pathology of shock part of a more general study of the syndrome; he, too, was in basic agreement with earlier authors although he emphasised strongly the pulmonary congestion and oedema.

Fazekas, of Szeged in Hungary, published in 1965 a brief outline of findings in an enormous mass of human material. His ninty-one deaths included post-operative shock, electrocution, trauma, burns, haemorrhage, toxaemia of pregnancy, accidental $BaSO_4$ embolism and a wide range of poisonings. He, unlike many of his predecessors, used control material from extremely abrupt deaths as a standard for comparison. He described the usual congestion and oedema of the lungs, bronchoconstriction, fragments of thrombus within vessels and occasional free hepatic cells within the pulmonary capillaries and alveoli. In the liver he found capillary, vein and sinus dilatation, arteriolar dilatation, endothelial separation and free liver cells within vessels. He also found granular changes within liver parenchymal and endothelial cells. In the brain, oedema was the predominant feature. Although he studied also the spleen, heart and kidney, his published account made no mention of findings therein.

More specific types of shock have been studied by some authors. Davis in particular in 1940 and 1941 produced dehydration shock by subcutaneous injection of 25% sodium chloride solution in dogs. The changes were generally similar to those described in human shock by Moon (1948). Cameron, Burgess and Trenwith (1946) made similar experiments in goats.

Hepatic Changes in Shock

There is much evidence to suggest that the liver can play an important role in the development of shock. Until quite recently much stress was put on the presence in that organ of vaso-active materials and in the dog the liver has been shown to be the seat of dramatic circulatory changes in anaphylactic shock.

Circulatory deficiency can induce fatty changes in the liver with considerable speed. Could the fatty liver seen in fatal decompression cases be evidence of such disturbance? Moon (1948) appeared to consider the hepatic changes as secondary. Just how rapidly can hepatic fatty change appear, whether by new deposition of fat or by 'phanerosis'?

Much of the attention to the liver in shock arose from studies on human burn fatalities. Belt, for example, in 1939 described massive necrosis resembling the pathology of yellow fever. Hartman and Romence (1943) among others, drew attention to the part played by tannic acid applied topically but acting as an unsuspected hepatotoxic agent. In their animal experiments they observed lesser changes when coagulants were not applied, but nevertheless congestion, granular, vacuolar and fatty changes were seen in early deaths. Baker (1945) analysed ninty-six fatal burn cases. Of these, thirty-two died during the first day. One showed possible necrotic changes in the liver, six fatty change. Of the latter, four were slight. As he pointed out at the time, there was no evidence as to the possibility that the fatty change antedated the burns.

Bywaters (1946) was primarily interested in the development of necrosis and the use of mitoses as indicants of regenerative activity. In his forty-two cases of death following extensive crushing or more general mechanical trauma, liver specimens were obtained by needle aspiration immediately after death, or the liver was infiltrated with fixative within one hour of exodus. No increased mitotic activity was seen in cases surviving less than six days. Necrotic changes were first fore-shadowed at eight and a half hours, but were not seen clearly before two days. No fatty change was reported.

Prior (1948) studied three groups of burn fatalities. Cloudy swelling and necrosis was common in coagulant-treated cases and fatty liver was seen in all fifteen cases treated with sulphonamides. No histological evidence of liver damage was seen in thirteen cases treated with bland substances, with survival times of six hours to thirty days.

Zamchek, Chalmers and Davidson (1949) detected what would appear to be extremely rapid changes in human liver. They took liver biopsies at the beginning of six abdominal operations and compared the appearances with fragments removed from the same six and nine additional cases at the completion of abdominal surgery immediately before suture. In all cases they showed inflammatory and necrotic foci with diapedesis of polymorphs. That this should occur in so brief a period is somewhat surprising, but it is probably entirely mistaken to consider the changes as due to shock, general circulatory disturbances or anaesthesia. It is far more likely that the appearances, in the superficial part of the liver, were due to handling and the application of hot packs.

Gillman and Gillman (1948) made a very detailed study of thirty-eight cases of fatal burning, none treated with tannic acid. In those dying within one to eighteen hours they found occasional very fine fatty droplets in hepatic cells, particularly in the centrolobular area. At eighteen to thirty-six hours the appearance was more widespread and coarser; at thirty-six to forty-eight hours the change was widespread and the droplets of fat often large. Abundant fatty deposition was never seen before the twelfth day. They summarised their findings by stating that the presence of fat indicated application of a stimulus not less than twelve hours earlier; large droplets meant at least forty-eight hours and "when an intensely fatty liver is discovered, it may be stated with some assurance that it is the consequence of reactions set in train at least some eight days previously".

Popper (1948) concluded from a very extensive study that he could detect differences in hepatic histology between instantaneous deaths and deaths following an agonal period in excess of ten minutes. He also came to the conclusion that central necrosis without cellular infiltration may occur agonally. He did not set a lower time limit for this change.

Ellenberg and Osserman (1951) studied liver necrosis in human shock. They found evidence of cell damage very rare in cases of shock lasting less than ten hours, uncommon in shock of ten to twenty-four hours and common after more than twenty-four hours. Malamud et al (1946) reported on 125 fatal cases of heat stroke. Liver changes other than congestion were not detectable in less than thirty hours. No mention was made of fatty degeneration.

Mallory (1949) as part of his comprehensive study on shock formed the opinion that, making allowance for pre-existing fatty liver, fat deposition in shock was minimal or absent if death occurred within eighteen hours.

What of animal studies? The general findings are in close accord with the examination of human material. Cameron and Karuneratne (1936) using carbon tetrachloride, a most active hepatotoxic agent, showed mitochondrial changes at one hour, congestion at four and a half to five hours, hydropic vacuolation and minimal fatty change at twenty-four

hours and central necrosis and fat deposition in mid-zone at three days. Hartroft (1950), subjecting rats to acute choline deficiency, found fine fatty droplets at twenty-four hours and large fatty vacuoles after one week. Gupta (1956) examined livers of rats poisoned with thioacetamide; only after nine hours was fine fatty vacuolation detectable. By comparison sheep show earliest fatty vacuolation eighteen hours after administration of carbon tetrachloride (Alexander and MacDonald, 1960).

The mechanism of hepatic dysfunction has been very fully reviewed by Shoemaker (1967). He concludes that acute hepatic sinusoidal congestion and cellular aggregation are the fundamental lesions.

To summarise the evidence, whatever the agent and degree of insult, fatty vacuolation in which droplets are large (for example, of nuclear size) and hepatic necrosis with cellular reaction appear to need considerably more than eighteen hours to develop. This must be taken to indicate that in almost all decompression sickness fatalities reviewed in Chapter 8, the hepatic fatty infiltration must have existed prior to the altitude exposure.

Some weight is lent to this suggestion in that two British cases have been subjected to liver biopsy, at the writer's suggestion, by Group Captain Kelly, an RAF Consultant Physician.

Case 12 (Chapter 6) suffered from chokes, visual disturbance and post descent shock after a test some four years after his in-flight incidents. Biopsy on the sixth day revealed considerable fatty change (Fig. 9-1). Case 5 (Chapter 3) also presented a similar picture on biopsy on the fifth day (Fig. 9-2). In both cases the pattern suggests prior fatty infiltration, but it is unfortunate that clinical consideration led to deferment of biopsy for so long.

Renal Changes

Reference has already been made to the autolytic-like renal appearances. Are these a part of shock death or do they indicate a specific pathological process?

Moon (1948) and several of the authors describing individual cases have called the condition 'lower nephron nephrosis', using the terminology coined by Lucké in 1946. Lucké looked for the common elements in the renal changes in 538 deaths in shock-like states. The picture he drew was of focal segmental degeneration of distal tubules, oedema and venous thrombosis, haem casts and little or no proximal tubule damage. He detected tubulo-venous fistulae as did Corcoran and Page in 1945. They, however, in experimental animals, observed more change in proximal segments.

Lucké's opinions have been challenged repeatedly. Bell (1950) commented on the term 'lower nephron nephrosis' as being "a disservice to renal pathology in that it has added confusion instead of clarity". Oliver, MacDowell and Tracy (1951) using microdissection of individual nephrons came to the conclusion that necrosis was randomly distributed throught the nephron.

Sevitt (1956 and 1957) has done much to sort out a confused picture. He has occasionally found a Lucké-type condition: he calls this "Diffuse distal tubular necrosis". It occurs in two to three days and is dominated by cast formation. In children the condition tends to be more focal, with fewer casts. "Proximal tubular necrosis" is used to describe a pathological picture indistinguishable from that seen in fatal altitude decompression sickness. Particularly interesting is the description of deep cortical and medullary congestion and superficial subcapsular sparing of tubular morphology.
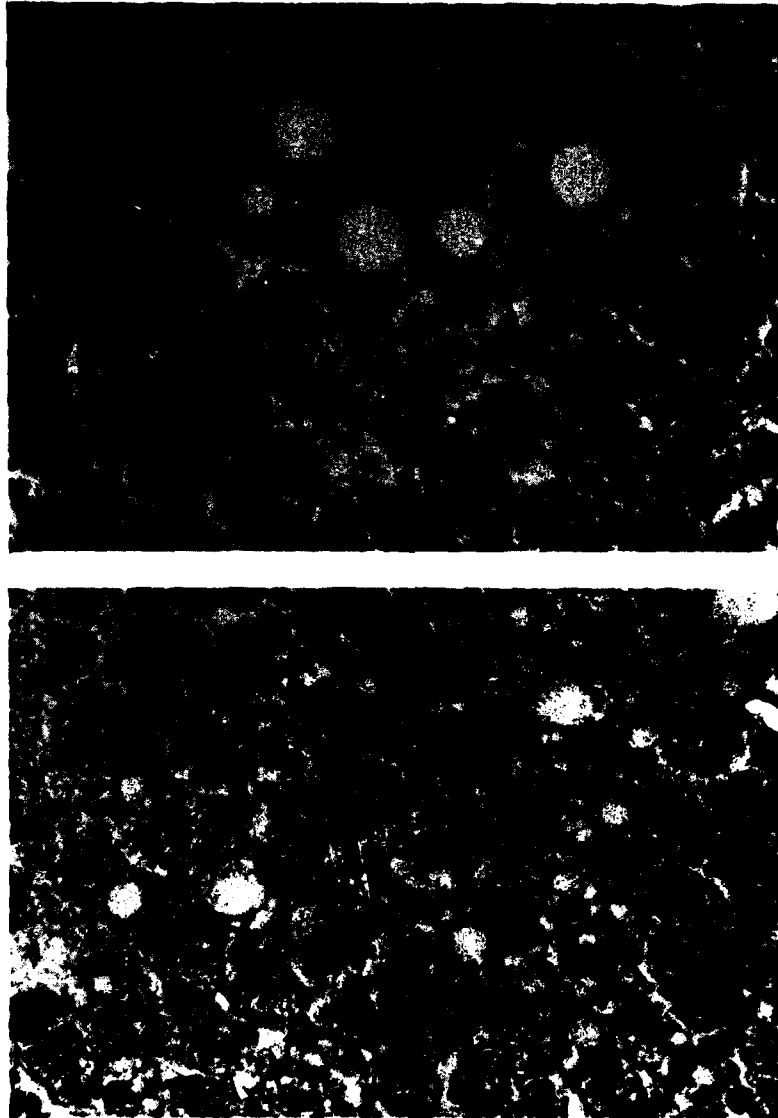
Fig. 9-1   Liver biopsy of Case 12;   sixth day of illness. H. & E. x 200.

Fig. 9-2 Liver biopsy of Case 5; fifth day of illness.   H. & E. x 100
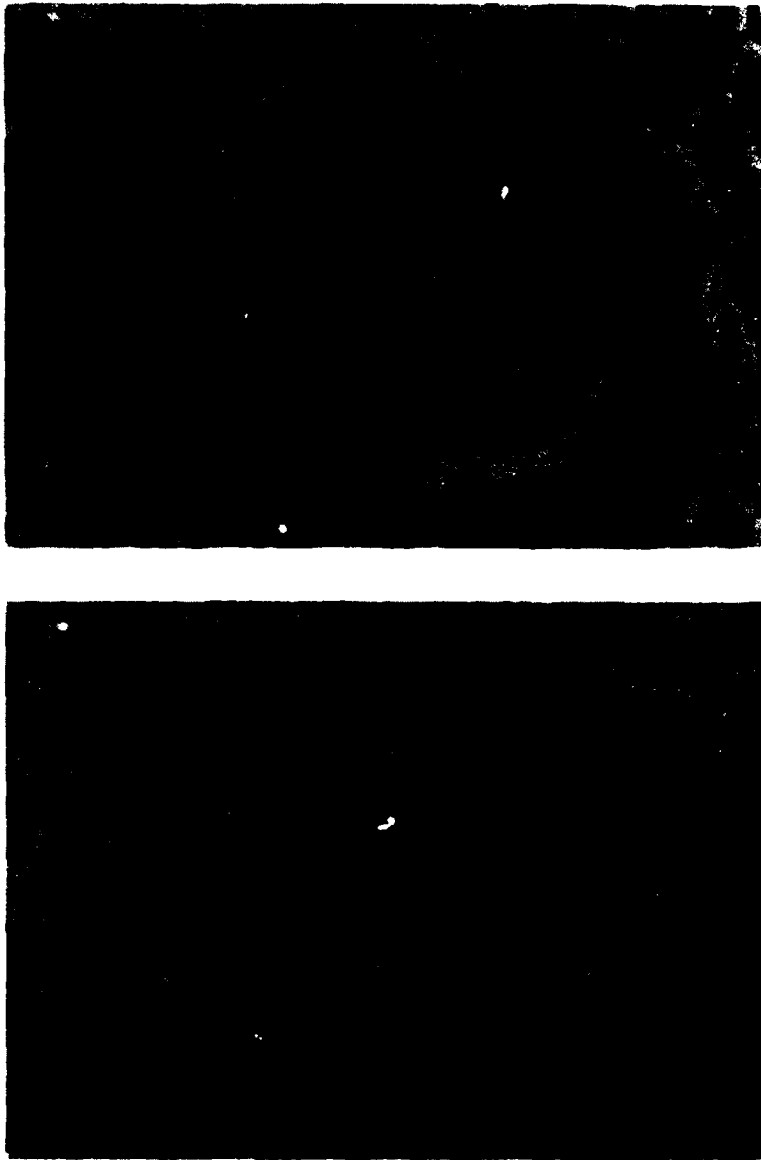(upper) and x 200 (lower).

Fig. 9-3 Afferent Arteriolar Dilatation; fatalities CS (upper) and LLC
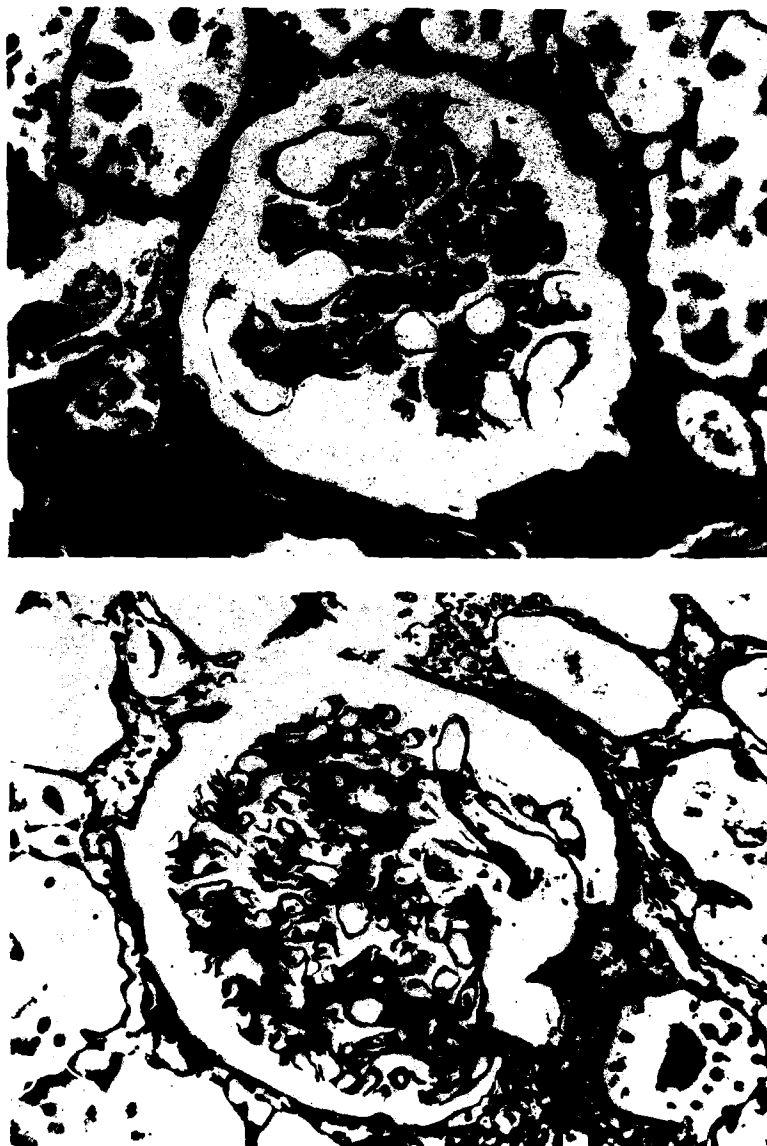(lower), H. & E. x 300 and x 185 respectively.

Fig. 9-4　Appearances due to dissolved-out fat emboli in glomeruli of
a compressed-air fatality.　Paraffin sections stained with
Picro-Biebrich x 620.
(Preparations kindly provided by Prof. A.C. Lendrum).

Sevitt has discussed the aetiology and has suggested, along with many other authors, that renal vasomotor activity associated with reduced circulating blood volume causes ischaemic anoxia and opening of the juxta-medullary shunts of Trueta et al (1947).

What of the time scale? Very little information is available in the literature, but it would seem possible that the changes seen could occur in the interval between altitude exposure and death. Could the changes be accentuated by post-mortem autolysis progressing more rapidly than normal? This would suggest a relationship between the delay between death and necropsy and the degree of pathological alteration. In fact, the kidneys of case E. R. T. where the delay was but two and a half hours and case '638482' where necropsy was performed within one hour of death, showed changes which are so advanced as to negate this theory. It might be thought that a hypoxic death, such as that associated with cyanosis in cardiorespiratory failure, might lead to accelerated autolysis owing to the presence of intermediary meta-bolites associated with anaerobic metabolism. In fact, Lindenberg (1956) reported briefly that in hypoxic death cellular detail was preserved and autolysis delayed.

We are therefore to draw the conclusion that the renal changes are akin to those of severe shock of certain types, but severe in degree and extremely rapid in evolution. Their mechanism remains rather obscure. It is generally assumed that renal vaso-motor activity occurs predominantly in the afferent arterioles of the glomeruli. Ischaemia of the cortex would be expected to be associated with afferent constriction and opening up of the juxtamedullary glomerular by-passes. However, in the British fatal case V and also in the US fatal case XVI quite remark-able afferent dilatation is evident (Fig. 9-3). (The identification of the afferent from efferent being made by elastin stains, the afferent alone having an elastic lamina). This appearance has also been detected in a compressed air death (Fig. 9-4). No description of this appearance has been found in the literature and its mechanism remains obscure. Its presence in a minority of cases must be taken as an indication that it is not an essential feature of this mode of death.

Specific Theories

Having considered those changes which may be regarded as non-specific and due to the mode of death, it remains for the mechanism whereby shock is triggered to be considered. Many theories have been advanced, but few stand critical exam-ination.

Gaseous Embolism

Cerebral Gaseous Embolism

From the earliest, severe decompression sickness has been attributed to cerebral gaseous embolism. Haymaker (1957) has, in particular, pursued such a concept. What is the strength of the evidence?

In altitude deaths no bubbles have ever been seen in the cerebral circulation except for a few in pial vessels - a site in which air is almost always drawn into the cir-culation when the calvarium is removed. The clinical picture hardly gives the impression of massive or focal cerebral embolism. In the former the victim generally collapses as though pole-axed; in the latter focal neurological signs are characteristic. The quantity of air necessary to cause death has been variously estimated. Fries et al (1957) gave a dose of 1.0 to 1.25 ml air/kg body weight as the LD50 for dogs in which air was injected via the carotid artery. Similar figures emerge from the work of Benjamin, Turbak and Lewis (1957). Davis and Willman found 1-5 ml/kg always lethal within twenty-four hours in dogs. Pate and Birdsong (1964) found over 3 ml/kg necessary to kill cats.

1.0

1.1

1.25 1.4 1.6

2.8 2.5

3.2 2.2

3.6

4.0 2.0

1.8
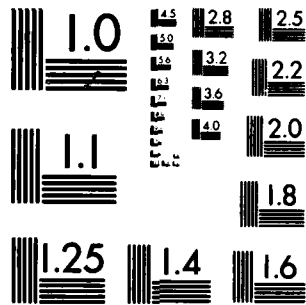
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

If one considers cerebral gaseous embolism seriously, it is necessary to postulate a site for bubble formation. Arterial blood should not be supersaturated to any degree at altitude except by the amount of ambient pressure drop which has occurred between the time that the blood passes the pulmonary capillary bed and the time that it reaches the periphery. There is plentiful evidence that blood desaturates with regard to dissolved inert gas almost completely during a single passage through the lungs. Therefore we should not consider bubbles arising in the arterial tree *de novo* except in extremely rapid ascents. A careful search of the literature reveals that in those animal experiments in which arterial bubbles have been clearly demonstrated, decompression has been extremely rapid. Examples are the papers by Wagner (1945) and Leeuwe (1961-62). The only evidence which really casts doubt on the idea of complete arterial equilibration in the lungs is that of Gramenitskii and Savich (1964) who observed bubbles to form in arterial segments completely isolated by ligature some minutes after decompression from high pressure. They postulated three possible mechanisms; non-completion of desaturation in the lungs, failure of the formed elements of the blood to desaturate and inward diffusion of gas from lipid-rich arterial walls. To this they should have added a fourth, more probable explanation; coalescence of extremely small bubbles which are not visible to the naked-eye and which had traversed the pulmonary bed before arterial ligature.

If bubbles do arise in the arterial tree or penetrate the pulmonary bed it is surprising that altitude cases do not show evidence of coronary arterial embolism, a very frequent case of death in arterial air embolism according to Durant et al (1949) and many other authors. The whole question of penetration or by-passing of the pulmonary filter will be dealt with elsewhere in this chapter. If arterial embolism were widespread, one might have expected to see some of the cardinal signs of the condition in at least some of the serious and fatal cases. These signs include bubbles in arteries of the retina, visible with the ophthalmoscope, Liebermeister's sign of focal pallor of the tongue and ECG signs of myocardial ischaemia. None of these has been reported. The only sign listed by Durant et al which could be invoked as a manifestation of air embolism in altitude deaths is skin mottling.

What are the results of the arrival of gas bubbles in the cerebral vessels? Almost all authors writing on decompression sickness seek to explain the latency and transience of neurological signs on a basis of arterial spasm. Villaret and Cachera (1939) in an extensive series of observations on dogs with transparent skull inserts showed, with excellent photographic evidence, that spasm never occurred as a response to gaseous embolism of the pial vessels! No evidence can be found for the response of intracerebral vessels as opposed to those of the meninges, but the overwhelming evidence for profound vasodilatation as the reaction to gas bubbles elsewhere in the arterial tree (Duff, Greenfield and Whelan, 1953 and 1954; Fleck, 1961; Bond, Durant and Oppenheimer, 1965; Baird, Miyagishima and Labrosse, 1964) would appear to make spasm unlikely in the extreme. Danis and Willman (1963) were interested by the discrepancy between the minor evidence of vascular occlusion revealed by angiography and the extent of histological signs of damage in gaseous embolism of the brain. In spite of the clinical evidence suggestive of oedema in man, the result of gaseous embolism in dogs was no increase in the water content of the brain at eight to twenty-four hours after such an instance. This is in contrast to the elevated brain weights in the four human altitude deaths for whom figures are available (Table 8-3).

Structurally, the picture of cerebral damage by gaseous embolism is clear-cut. The widely-reported findings have been summarised by Haymaker (1957) and by Brierley (1963). They include perivascular neuronal pallor and myelin rarefaction and geographical lesions of hemispheres, basal ganglia and cerebellum. They are, in fact, the extensive type of lesions seen in three of the seven in-flight

fatalities and one of the chamber deaths (Table 8-4) and to a much lesser degree, the first four chamber fatalities investigated by Haymaker and Davison (1950).

Do we have, therefore, convincing evidence of a primary role for cerebral gaseous embolism in fatal altitude decompression sickness? Unfortunately, we do not. Extremely careful neuropathological examination of the brains of seven of fifteen such deaths has resulted in complete exclusion of such lesions. This cannot be attributed to lack of time for the histological picture to develop; examination of Table 9-1 shows that not only do some of the late cases show no signs of damage, but the most extensive changes have twice been recorded in cases dying in less than twelve hours.

Table 9-1   Relationship between survival time and development of CNS lesions.

Lesions	Marked, widespread	Minor, focal	Absent
Under 12 hours	2	1	4
Survival time			
12-24 hours	1	2	2
Over 24 hours	1	1	1

Could cerebral air embolism in specific sites be reponsible for the clinical condition of post-descent shock? Pulmonary oedema, for example, can arise from interference with the cisternal region and the structures around the fourth ventricle (Cameron and De, 1949). The occurrence of fever might suggest hypothalmic damage. However, careful examination of these regions, eve ; in cases with survival for thirty-six hours or more has failed to reveal any significant lesions.

The whole matter of the aetiology of the cerebral lesions, even those of the most striking kind seen in fatalities numbers VIII, XII, XIII and XVI of Table 8-4, is extremely difficult to unravel. As has already been stated, the picture is very like that of gaseous embolism as classically described. However, a remarkably similar picture can be produced by hypotensive episodes. Adams et al (1966) have studied eleven cases of profound hypotension and it would appear from their observations that although the hypotension type of lesion might be confused with that of embolism, the distribution in the 'watershed' areas between the territories supplied by the anterior, middle and posterior cerebral arteries is quite different from that implied by the descriptions of the altitude deaths referred to in Chapter 8. In the experimental animal, however, the distribution is not always so clear-cut on vascular territorial grounds (Brierley and Excell, 1966; Brierley, personal communication) and one of the human cases of hypotension described by Wolf and Siris (1937) bears the most striking resemblance to those altitude fatalities reviewed by Haymaker (1957).

The Wolf and Siris's case was a patient who was undergoing section of the trigeminal nerve under local anaesthesia. Quite suddenly his blood pressure fell from a level of 175/90 to 100/60, and within 20 minutes to 65/40. Resuscitation raised the blood pressure again to 100/70 within twenty minutes, but the patient, who lost consciousness when the arterial pressure fell, never regained consciousness and died two days later. The incident which precipitated the hypotension in this and two other of Wolf and Siris's cases was middle meningeal artery section. This might well lead, under local anaesthesia, to vaso-vagal syncope, since puncture or section of an arterial wall often so results. Although the authors did not stress the point, one of the vital considerations in these cases is the posture. An arterial

pressure of 60/40 at cardiac level (as with a brachial cuff) is some 25 mmHg greater than that at a level one foot higher, as would apply here to the brain. Thus a cerebral arterial pressure of 35/15 may be assumed and this could be the reason for the cerebral damage observed. On the other hand, operations on the head and neck are a potent source of venous air embolism, (Cammermeyer and Adams, 1954; Hunter, 1962; Emery, 1962) and Wolf and Siris do not seem to have taken note of this possibility. Anatomically, the section of the middle meningeal artery would seem an unlikely locus for this case of air entry and the very profound hypotension without signs of cardiac dysfunction, apnoea or dyspnoea is unlike the type of case due to proven massive venous air embolism.

The relevance of cerebral hypotension in the sitting position and the altitude fatalities lies in the fact that of the four deaths with major cerebral lesions, three were in aircraft in which seat harness forcibly held the victim in an upright position. Bourne (1957) has shown how dangerous a vaso-vagal faint can be under such circumstances and Brierley and Miller (1966) have demonstrated the extent of cerebral damage which may occur. Alternatively, the same three cases, numbers XII, XIII and XVI in Chapter 8, had patent foramina ovale and as such may have been subjected to gaseous emboli in larger cerebral vessels than would be involved if gas had had to pass through the pulmonary vessels.

Thus we have two possible explanations, hypotension and embolism, for three of the four cases of gross cerebral damage. On the other hand, we have no explanation for the sparing of the brain in fatal cases XIV and XV, also seated in harness, or for the sparing of the brain of fatal cases IX and XVII, both of whom had proven atrial septal defects. It would appear that cerebral gaseous embolism is not the prime cause of most fatal cases of decompression sickness at altitude.

Generalised Gaseous Embolism

Could overwhelming gaseous embolism throughout the body be responsible for post-descent shock? Three approaches suggest themselves to the investigation of this postulate. They are the direct evidence in man, the evidence from animal and *in vitro* experiments and comparison with known cases of induced gaseous embolism.

So far as the first approach is concerned, there is absolutely no recorded evidence of bubbles at necropsy. on ophthalmoscopy or on cardiac auscultation. The latter has been extensively studied by Shivpuri et al (1959). The matter of neurohistological evidence of embolism has already been discussed. The only other relev: histopathological technique seems to be that suggested by Adebahr (1960) who described, in both experimental animals and accidental human deaths, spaces in blood-containing cavities with surrounding rings of white cells and platelets. These are claimed to be apparent even if death ensued within one minute of embolism. A diligent search of the human material, including the blood clot in atrial appendages, has failed to reveal any such change in fatal altitude decompression sickness.

What of animal experiments? The susceptibility of animals upon decompression from raised pressures is very varied, in general small animals being much more hardy in this respect than larger species. Kindwall (1962) made an interesting study on this topic. He found that if the assumption is made that saturation rates of tissues are proportional to metabolic rates, the small species were not gaining immunity by rapid gas exchange but were apparently able to surface with much higher gas tensions than larger experimental animals. The same concept would appear to apply to subatmospheric decompression. The writer has subjected rats to periods of one hour at 40,000 feet without apparent ill-effect and Gribble

(1954) was unable to provoke any reaction in guinea pigs under the same conditions. Daly and Fegler (1942) managed to induce some bubble formation in rabbits at 40,000 to 45,000 feet but these were hardly in a normal state, with opened abdominal cavities when decompressed. The American animal work during the World War II was generally unproductive of evidence for bubble formation under simple subatmospheric conditions except when very violent pressure changes were used or animals were subject to gross operative interference. (Catchpole and Gersh, 1947; Gersh and Catchpole, 1951; Blinks, Twitty and Whitaker, 1951).

Malmejac (1948) claimed to be able to demonstrate bubbles in veins and arteries of dogs decompressed with adequate oxygenation, to 33,000 feet or above, but others have found it impossible to confirm these observations. As has already been mentioned, Miller in 1944 reported on decompression of sheep from ground level to 31,000 to 46,000 feet, claiming fatal outcome in eleven of twelve animals, with bubbles in brain and heart, pleural effusions and splenic contraction. Unfortunately his protocols were far from a model of clarity.

Interest in dogs was revived by Leverett, Bitter and McIver (1963). They were able to show bubbles in venous cuvettes in animals decompressed to slightly above 40,000 feet, but it must be admitted that the operative interference of cardiac catheterisation, cuvette insertion, etc. may have influenced bubbles formation. These authors and others (Cockett, Nakamura and Franks, 1963) have found it necessary to resort to superatmospheric to subatmospheric decompression to provoke severe reactions in dogs and even then they have found prior splenectomy to be essential.

The war-time work of Newton Harvey (Harvey, 1944 and 1951) is vital in any consideration of animal research. He showed elegantly that bubbles will only form in supersaturated liquids when micronuclei either pre-exist or are induced by cavitation. Walder (personal communication) has recently repeated some of these experiments with identical results. Since micronuclei exist classically at interfaces, particularly where non-wetting surfaces meet liquids, catheterisation, cannulation or any circulatory by-passing procedure must immediately be regarded with suspicion. Even more suspect are *in vitro* experiments, such as those of Downey et al (1963) on serum in plastic cuvettes. There is certainly a marked contrast between the reports of bubbles seen in animals subject to operative interference before, during or immediately after decompression and the apparent indifference with which unanaesthetised intact animals will tolerate decompression.

Various authors have discussed cavitation as a possible source of bubble formation, even in the absence of supersaturation (Hugh and Fox, 1963). From the evidence of experiments on hydrodynamics, it would seem that surface irregularities and abrupt changes in diameter of pipes would be potent exciters of cavitation. As an example of the latter, many believe Korotkoff sounds heard distal to arterial compression by a cuff are due to cavitation. The lack of any apparent relationship between the presence of vascular stenoses or atherosclerotic plaques and susceptibility would seem to exclude these as potent factors and certainly no symptoms or signs, local or general appear to follow inflation of a cuff on the arm to such a pressure as to induce the production of Korotkoff sounds.

Experimental gaseous embolism has a vast literature. Durant, Long and Oppenheimer (1947), Durant (1953) and Bailey (1956) are excellent review sources. As has already been explained, on theoretical grounds venous embolism would seem to be the most likely form of gas release phenomenon in decompression sickness due to evolved gas. Massive introduction of gas into the venous system induces in man and in animals abrupt collapse, a pre-cordial "mill-wheel murmur", a dramatic rise in venous pressure and catastrophic hypotension.

Continuous slow infusion of bubbles or discrete low dosage with gas has been studied fairly extensively. Singh (1936) found rapid shallow breathing, reduced cardiac output and bronchospasm in cats. Dick (1939) observed in dogs cyanosis and pulmonary hypertension as well as the changes reported by Singh.

In the more active research field of particulate pulmonary embolism there has arisen conspicuous controversy between those who think the pulmonary hypertension so induced to be reflex in origin and others who believe in a purely mechanical mechanism. The arguments still continue (Parker and Smith, 1958; Hyland et al, 1963; Caldini, 1965). The opinion of Weidner and Light (1958) that reflex activity (as exemplified by contralateral response to embolism of one lung or part thereof) is a reaction to emboli smaller than 100 μ, would appear well supported by experimental evidence.

Other workers have concentrated more on ventilatory responses. Dunn (1920) made the pioneer observations on this topic, which has already been dealt with briefly in Chapter 4. Boyer and Curry (1944) showed that bronchospasm was predominant in embolism with small particles. Colebatch and his colleagues have made extensive studies with barium sulphate as a micro-emboli material of about 15 μ particle size (Colebatch and de Kock, 1963; Colebatch et al, 1964; Halmagyi, Starzecki and Horner, 1964; Colebatch, de Kock and Olsen, 1964; Nadel, Colebatch and Olsen, 1964) deducing that the massive alveolar duct and small bronchiolar constriction, which is the characteristic response, is mediated by histamine in the cat. Thomas et al (1964) came to the conclusion that the similar response to autologous clot embolism in dogs is 5-hydroxy-tryptamine mediated. Perhaps it is a little naive to conclude that the response is to mechanical stimulation. Although Colebatch et al describe barium sulphate as inert, Knisely et al (1957) claimed that in vivo it caused massive haemolysis. The writer has found that in dogs this material induces clotting when introduced via cardiac catheters. It could well be that much of the reaction is initiated by changes in the formed elements of the blood, particularly the platelets.

Does gaseous embolism resemble micro embolism or is it akin to large particle obstruction of the circulation to the lungs? Mandelbaum and King (1963) claimed to have shown that autonomic blockade by atropine and dibenzyline did not affect the vascular response; this would suggest that nervous-mediated mechanisms are not invoked. Anderson, Fritz and O'Hare (1965) considered that on the basis of immediacy of response, humoral mechanism were unlikely in the pulmonary hypertension response to bubbles. It is of interest that they found no difference between the response to air and preformed fine froth where similar volumes of gas were introduced. The writer has, in a series of experiments on dogs (Fryer, 1965), concluded that the response to air introduced into the pulmonary conus includes changes in resistance and compliance suggestive of a mechanism like that found by Thomas et al after clot embolism and Colebatch et al after barium sulphate embolism in the cat. However, the reaction is so much less in degree and duration than that to barium sulphate that the local humoral response must be regarded as slight. Similarly, Howard, Glaister and Stewart (1965) in experiments on dogs claimed the pulmonary hypertension response to be predominantly or entirely mechanical.

Experimental gaseous embolism techniques may involve the production of large bubbles compared with those arising from solution. Is there evidence of a micro-embolism type of response in experimental decompression sickness? Leverett, Bitter and McIver (1963) found in dogs similar responses to introduced bubbles and decompression from 6 atmospheres to 0.69-0.5 atmosphere. There is no recorded evidence of a marked bronchoconstriction response in animals exposed to altitude. On the whole it does not seem that exposure to altitude induces a response like that seen in barium sulphate or autologous thrombus embolism.

To summarise, there is little evidence, direct or indirect, of a massive pulmonary response to a minor degree of gaseous embolism in experimental embolism or induced bubble formation from supersaturation of the blood. Certainly there is no suggestion of a violent reaction akin to that shown by some animals to some forms of particulate micro-embolism.

Can the picture of severe and fatal decompression sickness be likened to that of venous or arterial air embolism? Certainly the dramatic arterial embolism associated with puncture of pulmonary veins during pneumothorax induction is totally unlike the effect of altitude (Durant, Oppenheimer, Webster and Long, 1949) in its immediate effect. Also, the generally described picture of massive venous embolism as caused by such procedures as insufflation of uterine veins, opening of veins in the head and neck of seated patients, admission of air under pressure during faultily administered transfusion etc. is much more catastrophic (Durant, 1953; Teare, 1959; Emery, 1962; Hunter, 1962). However, rather less well recognised is the fact that less massive and abrupt introduction of air by way of the veins can cause a very different clinical picture, much closer to that seen in decompression sickness. For example, Simpson (1958) states that he has evidence of latency of six to twenty hours between introduction of air and collapse.

Before completing the examination of the data from human accidental gas embolism, it is worth looking at the possibility of mixed venous and arterial embolism.

The Passage of Gas Bubbles through the Pulmonary Capillary Bed

It has often been demonstrated that bubbles can pass through peripheral capillary beds, or associated arteriovenous communications, to reappear in veins. Teare (1959) saw this in the leg, injection of air into the femoral artery being followed by bubbles in the femoral vein within five seconds. Pate and Birdsong (1964) saw bubbles in the jugular vein of cats within a second or two of intra-carotid embolism. Benjamin, Turbak and Lewis (1957) found that massive aortic embolism with 8 ml/kilo or more of air led to accumulation of gas in the right side of the heart. Fries et al (1957) in two of fifty-three dogs found that intra-carotid air found its way into the right ventricle and pulmonary artery.

Can bubbles pass through a normal pulmonary capillary bed? Apart from consideration of actual shunt communications, there is conflicting evidence on this possibility. Tureen and Divine (1936) noting cerebral damage after venous embolism dismissed transpulmonary passage and invoked cerebral ischaemia due to hypoxia. Rangell (1942), however, collected many cases from the literature, to which he added one of his own, in which there was either clinical or necropsy evidence of arterial gas embolism after undoubted venous air embolism by way of the uterine veins. Marchand, van Hasselt and Luntz (1964) could not show that air passed through the lungs in dogs but Villaret and Cachera (1939) showed quite conclusively that intravenous air administration was followed in about one third of their dogs by the appearance of bubbles in the arteries on the surface of the brain.

Pulmonary Shunts

Do pulmonary arterial emboli necessarily pass through the pulmonary capillaries? The question of pulmonary shunts or arteriovenous communications is highly debatable. Colebatch (1964) has stated that barium sulphate never passes the pulmonary filter, in spite of its small particulate size of approximately 15 μ.

Prinzmetal et al in 1948 injected suspensions of glass spheres at physiological pressures into the right ventricle, pulmonary vein, ear vein or jugular vein of

rabbits, dogs and one cat, and searched the macerated liver for evidence of trans-pulmonary passage. They found 160 μ - 290 μ beads in rabbits, 100 μ - 180 μ in dogs and 370 μ in the cat, to have passed into the liver and claimed this as evidence of shunts of such diameters. In fact, the evidence is not conclusive, since glass beads, being of much higher density than blood, can undoubtedly pass retro-gradely with respect to blood flow and they may well have passed down through the inferior vena cava to enter the liver via the hepatic veins. Tobin and Zariquiey (1950) perfused human lungs with suspensions of beads and claimed passage of spheres up to 500 μ in eleven of twenty-three experiments. They, however, used perfusion pressures of 50 to 300 mmHg, grossly unphysiological for the lesser circulation. The same authors (Tobin and Zariquiey, 1951 and 1953; Tobin, 1952) claimed to demonstrate shunts in pulmonary parenchyma and immediately sub-pleurally by injection of latex or vinyl acetate and subsequent dissection, but again their technique is open to question on the count of the grossly abnormal perfusion pressures. Rahn, Stroud and Tobin (1952) attempted to retrieve beads injected into the pulmonary artery by aspiration from a second catheter located in the aorta. Of hundreds of beads of 175 μ to 225 μ, one only was detected to have passed through the lungs under conditions of full oxygenation and two when the animal was given 10% oxygen in nitrogen. The authors studied the rate of passage of materials through the lung by cinefluorography and came to the conclusion that shunts opened only when a catheter was jammed into a pulmonary arterial branch. They concluded that mechanical irritation might lead to opening of pre-existing shunts. Niden and Aviado (1956), also using beads, concluded that in the dog shunts of up to 420 μ opened as a response to pulmonary hypertension or hypoxia.

Ring et al (1961) catheterised the pulmonary arteries of dogs and introduced poly-styrene spheres of much more reasonable specific gravity (S.G. 1.11) than glass and collected blood from the carotid arteries. Generally no spheres larger than 15 μ passed through in the first circulation (measured by recording the passage of simultaneously injected dye or radioactive red cells). By five minutes larger beads up to 80 μ appeared, but in all less than 1% of the particles larger than 15 μ seemed to find their way through the lungs. Hamlin, Marsland and Smith (1962) studied the pulmonary bed of three sheep. They used high density radioactive ceramic spheres which they sought in the body after injection into the jugular vein. Their failure to find any evidence of passage of beads of 52 $\pm$ 7 μ would at first seem to rule out the existence of shunts, but it must be noted that the animals were killed within sixty seconds of the introduction of the emboli. On the evidence of Ring et al (1961), it would have been better to have left the animals longer before sacrifice.

To summarise, it would appear that the lungs act as a remarkably efficient bubble trap, allowing few and predominantly small emboli through into the arterial circulation. Nevertheless, in man, massive pulmonary embolism which is not immediately lethal can be followed by signs and symptoms of systemic spread.

Apart from hall marks of cerebral arterial embolism in the shape of focal neuro-logical signs, there are other features common to the presence of bubbles intro-duced directly into pulmonary veins and thence the aorta and to what would appear to be slow trans-pulmonary passage of gas. That these signs are present also in decompression sickness revives what must obviously have betrayed a flagging credulity on the part of the writer in the role of gaseous embolism in this condition.

Group Captain J.N. Cooke, FRCP, has been responsible for the clinical care of a number of cases of decompression sickness and in collaboration with the writer, has established a pattern of investigation which has become routine. In 1962, he was faced with a fascinating opportunity to make a contribution to our knowledge of gaseous embolism. A young airman undergoing antrum lavage suddenly collap-sed when air was introduced into his maxillary sinuses under pressure. Clearly

he had suffered the recognised risk of this procedure, venous air embolism. Immediate resuscitation restored his airway and tided him over until spontaneous respiration recommenced. Investigation of this patient during his subsequent illness showed that he exhibited three of the cardinal signs of decompression sickness - haemoconcentration, pyrexia and leucocytosis. Neurological complications suggested that some bubbles had, by one route or another, entered the cerebral circulation.

In 1966, a young sub-aquatic enthusiast suffered a serious accident when, after a mishap with his equipment, he surfaced rapidly from a depth of over 150 ft. The duration and depth of his dive would suggest that he was not likely to suffer immediate violent manifestations of decompression sickness and his colleague who surfaced shortly afterwards was unaffected. The patient collapsed immediately on breaking surface and closed cardiac massage and mouth-to-mouth resuscitation were necessary. He undoubtedly suffered the well-recognised complication of rapid ascent with inadequate exhalation, arterial gaseous embolism (see page 226). He too developed extreme haemoconcentration (PCV of 68%), leucocytosis and hyperpyrexia (Cooke, personal communication).

It is tempting on the above evidence to suggest that in the most severe forms of decompression sickness, large scale pulmonary gaseous embolism with transpulmonary passage of gas, via capillaries and possibly via shunts, brings about widespread capillary permeability change, leucocytosis and pyrexia. Focal cerebral embolism in some cases may be a manifestation of a generalised process of arterial embolism rather than the specific cause of the illness.

Embolism via the Vertebral Plexus of Veins

Haymaker and Johnston (1955) and Haymaker (1957) drew attention to the proven anastamoses between the spino-vertebral veins and the azygos system. In the grossly abnormal circumstances of the animals generally illustrated (prior pulmonary venous obstruction by ligature) pathways between pelvic and abdominal veins, vertebral veins the azygos veins and thence via the enlarged bronchopulmonary venous communications to the left heart may be demonstrated in dogs. In more normal conditions the so-called Batson plexus of communicating veins may allow embolic dissemination of tumour cells, infection and thrombi between the abdominal and pelvic veins, the spino-vertebral veins and the azygos system. It is possible that, as Haymaker suggested, gaseous embolism may by such a route embarrass the venous drainage from the spinal cord. It is not apparent, however, that in normal anatomical circumstances this system can be involved in veno-arterial shunting. Admittedly, Wack, Duboque and Wyatt (1958) could, in dogs, trace the passage of radioactive thrombi from femoral veins to the vertebral veins, the lungs, the liver and the kidneys, but it must be noted that all their experimental animals had undergone ligation of the inferior vena cava one to five days earlier.

Thus, the vertebral venous plexus would seem to have a minor role, if any, in any postulated veno-arterial bubble passage in decompression sickness.

Patency of the Foramen Ovale

Great hopes of a final clue to the cause of post-descent shock were raised when Haymaker, Johnston and Downey (1956) reported patency of the foramen ovale in their two fatal in-flight cases (fatalities XII and XIII of Chapter 8). Here at last

was an explanation for individual susceptibility - paradoxical embolism from venous circulation to arterial tree, by-passing the pulmonary capillary bed. Hopes were shattered when Mason and the writer examined the heart of fatality case XIV (V. K.) and the foramen ovale was found to be indisputably closed. As can be seen from Table 8-3, the score among hearts carefully examined stands at five patent to two closed and two probably closed. The heart weights suggest that no more than two of the cases of patency were likely to have been functionally open.

That patency of the foramen ovale could lead to heightened risk of systemic embolism from thrombo-phlebitis of leg and pelvic veins has been long established. Naville and Fromberg, in 1913, drew attention to a similar role in fat embolism in a single case and further reference to the risk in this type of embolism has been made by Winkelman (1942), Hermann (1948) and Kershman and Haddad (1952). Cohen al (1951) and Vigouroux and Nivelleau (1960) have drawn attention to the possibility of paradoxical gaseous embolism via septal defects. The existence of a valve-flap guarding the commonest kind of patency (Patten, 1938) does not exclude trans-septal traffic. Although the left atrial pressure is normally higher than that in the right atrium and the valve is always on the left face of the orifice, as has been pointed out by Haymaker, Johnston and Downey (1956), pulmonary embolism in itself may cause pulmonary hypertension and reduced pulmonary blood flow with reversal of the atrial pressure relationship, opening of the valve and direct vein-to-artery shunting.

Care should be exercised, however, on two counts. Firstly, a defect of the septum need not give rise to paradoxical embolism. Schmidt, in 1958, described a fatality attributed to bone marrow embolism in a patient following thoracotomy. The victim, who underwent operative exploration for possible cardiac surgery. became ill on the second post-operative day, became febrile, cyanosed, dyspnoeic and died on the 4th day. Sections of lung showed bone marrow fragments in many branches of the pulmonary arterial tree. No such embolism was found in the kidneys, liver or spleen and yet the atrial septum had a 15 mm defect which had obviously been the site of shunting in life, since the heart was considerably enlarged (500 gm). Gross (1934), however, showed in simple but elegant experiments that at differential pressures between atria of no more than 10 cm of water, gum tragacanth 0.32% (of similar viscosity to blood) passed between atria by way of valvular defects at a measurable rate, when the right-sided pressure exceeded the left. At 40 cm of water pressure the flow could reach 500 ml/min. If the pressure gradient was reversed, flow did not occur until the pressure difference reached 40 to 50 cm of water. Artificial emboli passed through the aperture when the whole system was agitated. This experimental work is difficult to reconcile with the clinical case of Schmidt. Perhaps it indicates that in the case described, atrial pressures remained balanced.

Secondly, patency of the atrial septum is remarkably common. Ogle (1857) observed defects in thirteen of sixty-two hearts, Parsons and Keith (1897) found an incidence of 26% in 399 hearts, Fawcett and Blachford (1901) found 31.4% in 306 and Seib (1934) 17% in 500. In those series in which measurements were made, approximately one half of the defects were 5mm or more in diameter. Although the count of 5/9 patencies in fatal decompression sickness strongly suggests a significant relationship between the two conditions, it must be emphasised that the 25-odd percent of patency in the population does not tie-up with the 0.015% incidence of decompression collapse calculated by Adler (1950).

To summarise, patency of the atrial septum is probably significantly common in decompression fatalities, but it is neither essential for the atrial septum to be patent to become a victim nor particularly hazardous to possess such a defect. This cardiac anomaly must be regarded as a common feature of the condition of post-descent shock, but not a prime cause.

Autochthonous Bubbles

The possibility that bubbles arising in tissues might give rise to local disturbances without passing through vascular channels, has long been discussed. In animals decompressed from high pressures this can undoubtedly occur. Hill (1912) was able to demonstrate bubbles in cat liver and kidney after very rapid decompression from 8 atmospheres. Boycott, Damant and Haldane (1908) had little success in searching for extravascular bubbles, however, in mice, dogs and goats decompressed from lesser pressures. They could find no such lesions in sixteen tissues but could demonstrate quite remarkably large spaces in the spinal cord and once in the brainstem of goats (Boycott and Damant, 1908).

In more recent times Catchpole and Gersh and their collaborators have carried out most extensive studies, using freeze-drying methods of preparation. Particularly striking were their claims to have shown the genesis of bubbles in adipose tissue cells, with coalescence and rupture into venules. (Gersh, Hawkinson and Rathbun, 1944). Unfortunately, they were unable to find such appearances in decompression to altitude (Catchpole and Gersh, 1946). The presence of bubbles in the myelin sheaths of guinea pig nerves after decompression from high pressures was also claimed by Gersh, Hawkinson and Rathbun. The only illustration was a drawing and the fact that the bubbles as shown are in the Schwann cells and quite outside the myelin sheaths does not inspire confidence in the judgment of the authors.

Histopathological studies on human material from altitude fatalities (Chapter 8) show no real evidence of cellular damage except that minor focal necroses in liver and myocardium could perhaps be so caused. There is certainly no evidence of such damage in the majority of cases.

Autochthonous bubbles within and perhaps between cells must be presumed to cause anatomical or physiological disorders of those cells, if they are to lead to generalised manifestations of shock. Thus one should be able to detect in the circulation or at sites remote from the bubbles, materials normally confined to the regions of cellular damage. That this might be so is suggested by the finding of fat embolism (Table 8-4). This particular matter will be dealt with in a following section of this chapter. Intracellular structures such as nuclei have not been detected in abnormal sites. Whole cell embolism likewise is absent. Quite commonly free liver cells are seen in hepatic vessels, but this a common post-mortem appearance (Fazekas, 1965). Soluble materials which might indicate cellular damage are numerous. The two which spring to mind are potassium and adenosine compounds. The former has only once been detected as having been elevated in the large number of cases investigated. The latter, together with many other materials, were diligently sought by Gribble (1954) in guinea pigs exposed to altitude, with entirely negative results. As has already been mentioned in Chapter 8, transaminases too have not been found to be present in abnormal amounts in clinical cases.

Thus one of the most attractive theories, so elegantly expounded by Sproull (1951) and Rait (1952) remains unproven if not categorically excluded.

Fat Embolism - General Consideration

Haymaker and Johnston (1955) thought that they were the first to draw attention to fat embolism in decompression sickness. Although Haymaker himself, together with Davison had observed fat emboli in the first five fatalities recorded in the literature (1950), they had not commented on possible significance. In fact, Muir cited decompression from high pressure as a cause of fat embolism in 1941, drawing on material obtained by Lendrum. The latter h.'s kindly given the writer sections from this case, which was that of 44-year old ompressed-air worker who collapsed shortly after a routine decor ion. die some ten hours later

despite recompression.   At necropsy he was found to have one kidney almost totally destroyed by tuberculosis.   No lethal lesion was detected.   The sections of the healthier kidney show quite clearly (Fig. 9-4) the gross extent of the fatty material impacted in the glomerular tufts.   They also show, interestingly enough, afferent arteriolar dilatation (Fig. 9-3).   There was also capillary fat embolism of the brain in this case.

The theory of fat embolism as an aetiological mechanism has been actively supported by several workers.   Rait (1959) became the leading exponent of this theory and Stutman (1960) advanced it to the exclusion of others.   Hardie, Cullen and Bryan (1961) also expressed belief to the extent of stating that "fat embolism appears to play an essential but mysterious part in this condition".   Wünsche and Henn (1962) reviewed the evidence from the two fatalities reported by Pioch (1960) and Henn (1962) (see Chapter 8).   They claimed to be able to induce fat embolism in rats decompressed rapidly from 12 atmospheres and in rabbits, guinea pigs and rats decompressed to 59, 000 feet.   The former pressure change is extremely high and the starting level is in the range where toxic effects of oxygen and nitrogen are important;   the latter altitude is such that anoxia must be extreme, in that the atmospheric pressure is less than 10 mmHg. greater than the vapour pressure of water at body temperature and water vapour and CO_2 must swamp the alveoli to the exclusion of oxygen.

The extent of the interest in fat embolism in decompression sickness is exemplified by the selection of the topic for review in this context by Wittmer in 1962.   In 1963, Fischer carried the idea to a new extreme.   He attempted to diagnose decompression sickness post hoc from minimal embolism in tiny tissue fragments from the disintegrated body of a student pilot whose pressurised aircraft had crashed from an altitude no greater than 19, 000 feet, without any radio indication of distress.   The evidence is tenuous in the extreme, but this paper reveals the effect of the arguments advanced by Rait, Stutman and others.

What is the strength of the evidence and how do accidental and experimental fat embolism resemble the picture of decompression sickness?

Fortunately for the writer, the vast, scattered and controversial, if not downright confusing, literature has been scientifically sifted and brilliantly reviewed by Sevitt (1962).   A few important concepts must be mentioned, however.   For example, Harman and Ragaz (1950), in investigating the pathology of experimental fat embolism in animals, drew attention to the possibility that lipase in lung tissue might liberate highly toxic fatty acids from lodged droplets in the pulmonary vessels.   This idea has been avidly supported by Canadian workers.   Halasz and Marasco (1957) have, however, in careful work in dogs, shown no evidence of chronic inflammatory lesions such as might be anticipated to have arisen. Paredes et al (1965) demonstrated that intrapulmonary breakdown does occur, as revealed by the passage of radioactive Iodine[131], from a firmly bonded position in triolein emboli in the lungs to the thyroid gland within forty-eight hours.   No radioactivity corresponding to passage of intact emboli through the lungs to the brain could be detected.

It would seem fortunate indeed that the pulmonary filter is so effective in retaining fat;   Lowenfels et al (1963) showed that intra-arterial fat emulsion is ten times more active than the same material by the venous route, in terms of mortality. Branemark and Lindström (1964) showed a possible mechanism in that fat particles of 5 μ or larger in the finer blood vessels of the rabbit, coalesce and form rigid microemboli with cellular aggregates.

Where does the fat, which is undoubtedly occasionally seen in fatal altitude decompression sickness cases, arise? Here there are four distinct possibilities. Chylomicron aggregation, on which has been centred prolonged controversial argument, has probably a role, but only as a secondary phenomenon. The three more probable sources are the adipose tissue, bone marrow and the liver.

Fat Embolism from Adipose Tissue

Mention has already been made of the work of Gersh, Hawkinson and Rathbun (1944) in which the sequence of events of cell rupture due to bubble formation, bubble coalescence and incursion of gas into venules was described (albeit in a conjectural fashion according to the later writing of Catchpole and Gersh in their chapter in Fulton, 1951). Strangely they made no mention of fat embolism in their very extensive studies. They did, however, mention petechial haemorrhage in the adipose tissue in their animals decompressed from high pressures, as did Hill referring to decompressed domestic pigs (Hill, 1912). The absence of such petechiae studies on animals and man is remarkable (one fatal human case had mesenteric ecchymoses). Of all animals, the most prone to develop bubbles in adipose tissues must surely have been the extremely obese hyperglycaemic mice of Antopol et al (1964). In their very comprehensive study, however, these workers made no mention of fat embolism.

Therefore, it seems that the evidence for the liberation of fat from adipose tissue into the circulation is almost entirely negative.

Fat Embolism from Bone Marrow

In spite of all the arguments advanced to the contrary, bone marrow seems to be generally accepted as the prime source of fat embolism after trauma (Sevitt, 1962). Gersh (1945) demonstrated that bubbles could arise in bone marrow in animals decompressed from raised pressures, as also did Colonna and Jones (1948) and gas liberation could clearly lead to escape of fat into sinusoids. Kalser et al (1951) claimed, very unconvincingly, that exposure to altitude resulted in slight alteration in intramedullary pressure in bone.

Not only can fat be liberated from marrow; actual fragments of haematopietic tissue and even trabeculae can enter the circulation to appear in sections of lung (Lindsay and Moon, 1946). There are many such instances recorded after fracture; so much so that Mason (1962) has made great use of the technique in the differentiation of ante- and post-mortem trauma. Cases have also been reported after lesser degrees of violence, even without apparent fracture, as in lumbar puncture (Polayes, 1953) and manipulation of ankylosed joints (Gleason and Aufderheide, 1953). Rarely, emboli pass through the lungs into the arterial circulation to lodge in the brain or kidney (Rappaport, Raum and Horrell, 1951).

Can decompression liberate such tissue fragments? Mazzella and Paolucci (1961) found primitive cells in the circulating blood of rabbits after extremely rapid decompression to altitude. Clay (1963), studying tissues from animals subjected by Leverett, Bitter and McIver (1963) to decompression from 6 atmospheres to 10,000 to 15,000 feet, found fat emboli in lungs of twenty-eight to thirty-one dogs, bone marrow emboli in six and possible bone marrow emboli in eight. Fat emboli reached the kidneys in ten and the brains of three. Cockett, Nakamura and Kado (1965), using very similar techniques also claimed to find bone marrow and fat emboli in the lungs of dogs.

The writer has searched lung sections of fourteen human altitude fatalities and compressed air deaths, without finding a single bone marrow fragment. Admittedly the detection of these embolic scraps of marrow is not easy, but considerable

practice has been gained with material from traumatic deaths in accidents. To what, if anything, can this discrepancy between man and animals be ascribed?

Firstly, the severity of the decompression of the experimental animals is formidable. Secondly, necropsy of the animals was possibly often carried out very soon after administration of a lethal dose of an anaesthetic agent, in which case some residual circulation may have existed when the thorax was opened. Thirdly and probably most significantly, almost all the dogs had been subjected to splenectomy some days before decompression and it is not hard to imagine displacement of marrow fragments from ribs during the use of abdominal retractors at operation.

Thus, there is no evidence in man, either for or against bone marrow as the origin of fat embolism in decompression sickness.

Fat Embolism from Fatty Liver

The fatty liver is a strange organ. Individual cells of the parenchyma may apparently be reduced to a tenuous membrane-like structure surrounding huge aggregates of fat and yet the organ, as a whole, would appear to function remarkably well in a large proportion of cases. On the other hand, it has been recognised for a number of years that a proportion of those persons with fatty livers are subject to sudden and unexpected demise. This is particularly so when alcohol is involved as the agent responsible for the liver changes.

Graham, in 1944, collected eleven unexpected deaths in young alcoholics, all with fatty livers. He noted that both the mortality and the degree of hepatic fatty change appeared to be seasonal, both being less common in summer. He could suggest no definite mechanism.

Cammermeyer and Gjessing (1951) appear to have been the first to suggest fat embolism from an increased liver fat content, without trauma. They recorded a sudden collapse and fatal convulsions in a mental hospital patient, who was found at post mortem to have pulmonary and cardiac fatty embolism and also a grossly fatty liver. They postulated that fat could have left the liver to become dispersed through the blood stream, with resultant cardiac dysfunction. There followed a number of reports of such deaths, although in many cases authors appeared not to have been aware of the earlier report by Cammermeyer and Gjessing. Durlacher et al (1954) collected twenty-five deaths of alcoholics associated with fatty liver and pulmonary fat embolism. Fadell and Sullivan (1957) quoted further cases, Lynch, Raphael and Dixon (1959) made a large survey, with a series of controls and single cases were described by Kimble (1961) and in an anonymous report in 1962 from the Massachusetts General Hospital. Hill (1961) wrote of a death in a child of nine with a steroid-induced fatty liver, in whom massive pulmonary fatty embolism was found.

On the whole, such cases show predominantly embolism of the pulmonary bed with little or no evidence of spread into the systemic circulation.

Durlacher et al (1958) suggested that mild trauma or unspecified intrahepatic pressure changes might release fat from liver deposits into the circulatory system. In particular they draw attention to the escape from areas of what they called "extracellular lipohepatosis". This condition is very like that described by Hartroft as occurring in choline-deficiency in rats (1949). He found that, in this species, fatty cells lose their integrity and coalesce until fatty cysts, surrounded by multinucleated rims of cytoplasm from fused cell bodies, are formed. These cysts he proposed to call lipodiastemata, but the term never gained wide popularity (Hartroft, 1950).

Hartroft has, over a number of years, made an extensive study of the pathology of the choline-deficiency fatty liver. He has shown how large cysts, equivalent to 350 to 400 normal cells in volume, can be formed after about six weeks on an appropriate diet. Occasionally such cysts rupture into bile ducts or vessels (Hartroft, 1950). The fat so liberated lodges in lungs, kidney and heart tissue (Hartroft and Ridout, 1951; Hartroft and Sellars, 1952). Such cysts have been shown to exist in human cirrhotic fatty livers (Hartroft, 1953 and 1954) and it has been suggested that much of the pathology of some diseases associated with fatty liver may be attributable to the cycle of formation, rupture and resorption of fatty cysts, with cirrhosis, embolic phenomena and the organisation of renal glomerular emboli to produce the Kimmelstiel-Wilson lesions of diabetic intercapillary glomerulosclerosis (Hartroft, 1955; Raphael and Lynch, 1958).

What is the supporting evidence for such a chain of events? Owens and Sokal (1961) claimed to show that fat was released from perfused fatty livers of anaesthetised choline-deficient rats. Unfortunately it is not easy from their illustrations to differentiate between true emboli and coalescence of droplets in lipaemia. Owens and Northington (1962) could however cause what would appear to be genuine embolism by severe trauma to the livers of anaesthetised rats with a choline-deficiency produced fatty liver. Mild trauma (the degrees were not very clearly defined) caused no such embolism.

That a simple relationship between fatty liver, lipaemia and fat embolism exists had been challenged. For example, Kent (1954) could find very little evidence of emboli in fifty-three diabetics at post-mortem, although all could be assumed to have been subject to high blood-fat levels. He made no detailed comment on the liver in his cases, but Cuppage (1963). prompted by a case, surveyed thirty-eight poorly controlled diabetics and found almost one-third to have evidence of fat embolism. It was not possible, however, to correlate the degree of embolism with the severity of the liver change. Hendrix and Fox (1964) found in a large series that, in general, obesity and fatty liver tended to predispose to fat embolism.

To summarise so far, there is evidence of fat embolism from fatty cysts in choline-deficient rats, possibly accentuated by local trauma to the liver and enough cases have been reported to suggest that in alcoholics sudden and unexpected death may occur either in association with or possibly even caused by fat embolism. From evidence already presented in Chapter 8, pre-existing fatty liver is extremely common, if not universal, in decompression sickness deaths following exposure to altitude. It is also recorded in compressed air workers dying after a routine decompression from raised pressure (Sillery, 1958; Bennison, Catton and Fryer, 1965). Fat embolism is also common, but definitely not universal in both classes of case.

Evidence has already been produced in this chapter to suggest that fatty liver precedes rather than results from the fatal illness. Rait (1959) built a complete hypothesis around this concept but was perhaps a little less objective than might be hoped. He dealt at length with a case of a man of proven susceptibility (a single in-flight occurrence) who was clinically suspected to have a fatty liver, was proved to have such a condition by biopsy and who later had both a normal biopsy appearance and an improved altitude tolerance. Dietary deficiency was postulated for the fatty change. Apart from nationalistic bias, the evidence for the hypothetical deficiency having arisen during service in England is very poor. The dietary chart produced by Rait himself shows no lack of essential materials other than very minor discrepancies between recommended and actual calcium and riboflavin intakes. The diet on return to Australia was still calcium deficient and basically differed only in a reversal of the rather high carbohydrate to fat ration in England. The liver biopsy certainly showed fatty vacuolation, but it was performed thirty-five days

after the in-flight incident. No details are given of dietary changes other than that "... his diet had been very good, with the lipotropic factors well supplied" and it is tempting to suggest that the reversion of his hepatic histological appearance may have been associated with reduction of his beer intake from "about six glasses" a day to nil.

There is much, nevertheless, to commend the basic theory of Rait, later so avidly supported by Stutman (1960). For example, the writer's Cases 5 and 12 whose liver biopsies are illustrated in Fig. 9-1 both had extremely tender areas to pressure and percussion which could be seen to correspond to the shape and size of the liver. The edge of that organ was also very tender to palpation in full inspiration. The large fatty droplet in the hepatic cell appeals to the imagination as a source of disturbance in decompression. The lipid has a high capacity for dissolved inert gas, the cytoplasm looks tenuously stretched over the droplet and can be imagined to be liable to burst if a bubble were to grow within the fat. Subsequent discharge either directly into the hepatic sinusoid or via Disse's space into the lymphatics and thence the veins is certain.

Histologically, the evidence for fat release from a fatty liver is poor. If fatty cells burst, releasing fat into sinusoids, it is surely probable that red cells should occasionally enter the space left in the parenchymal cells. This has been carefully sought but never seen. Inflammatory reaction within the liver might be anticipated, but is rare and unrelated to time of survival or interval before biopsy. Finally, the quantity of fat liberated in human fatal cases, whatever the source, is minute and, indeed, in many cases a diligent search has failed to reveal any fatty emboli at all. Sevitt (1962) is convincing in his arguments that pulmonary fat embolism, however heavy, is rarely if ever fatal and that systemic embolism of severe degree is necessary to evoke the clinical picture of cerebral irritation, fever, peterhial haemorrhage and shock. Could it be that, for some reason, the true extent of embolism has been underestimated in altitude deaths?

Ancillary evidence of fat embolism may be sought in both clinical and pathological fields. Fat may be found in the sputum (Noessle, 1951) and in the urine (Glas, Grekin and Musselman, 1953) and in the retinal vessels on ophthalmoscopy (Alexander, 1960; McLenachan, 1960). All three techniques have been applied to a large proportion of RAF cases of post-descent shock admitted to hospital. All have proved entirely negative. Histologically, Russell (1941) has used frozen sections of the choroid plexus as a tell-tale filter for evidence of cerebral fat embolism. The writer has searched sections of this tissue in three altitude fatalities and one compressed air fatality with completely negative results. Cammermeyer (1953) described disseminated fibrin thrombi in association with cerebral fat embolism and Jaques and Saini (1962) have demonstrated inflammation and vascular cuffing in the lungs of dogs with experimental fat embolism. The pathological picture in man, already described, does not tally.

The biggest stumbling-block in the way of any theory based on fat embolism from the liver or any other source, is the paucity or absence of histological evidence of embolic fat in fatalities. To overcome this, Rait (1959) and others have supposed that a combination of fat and gas emboli, together with intracellular materials of all kinds, find their way into the circulation. Thus fat emboli may be only tokens of a much more serious process.

We have already dealt with the lack of direct evidence of gaseous embolism; what of combined embolism? The obvious answer is to assess whether fatty liver can be the source of such material in sufficient quantity and whether decompression liberates material from hepatic parenchyma.

So far as the first question is concerned, certain deductions may be drawn. Estimates of the fat content of fatty livers vary, but it would seem that 25% by weight represents a very advanced degree of infiltration. In the case of a human liver of 2,400 gm (about 30% above normal maximum), this would represent 600 gm of fat, which in turn with a density of 0.93 would have a volume of 645 ml. Vernon (1907) showed that fat dissolved nitrogen to the extent of about 5.1 ml per 100 ml when exposed to air at 1 atmosphere pressure. Thus, the fat content of a fatty liver would contribute some 33 ml of nitrogen (NTP). The total nitrogen content of an adult person is generally stated to be approximately 1 litre. Therefore the actual volumetric capacity for extra nitrogen due to fatty change in the liver is very small, of the order of 3.3%.

Animal Experiments

To test the second proposition, the vulnerability of the fatty liver, it would seem reasonable to assess the reaction to decompression of animals with induced fatty livers. Rait (1959) referred briefly to inconclusive experiments along these lines. The writer, in fact, carried out rather more extensive studies in 1956-57. They are described below.

Dietary Methods - It was decided that choline deficiency was not the most desirable method of production of fatty liver, since it may result in more widespread alterations in fat metabolism than could be expected to account for the type and degree of fatty change found in otherwise apparently healthy men. Hartroft (1963) has shown, for example, that by electron microscopy extensive mitochrondrial changes in liver cells can be demonstrated in choline deficiency. These alterations are not present in equally fatty liver cells resulting from starvation or high fat and carbohydrate intake.

It was established in preliminary experiments on weanling and young adult rats that the following diet (Table 9-2) recommended by Sutherland (1956), would regularly produce fatty livers with little evidence of other pathology.

Table 9-2   Sutherland diet - composition by weight

Hard fat (suet)	65%
Casein (powder)	21%
Crushed oats	6%
Cod liver oil	4%
Mineral salt mixture	4%

The mixture, well blended, can be chilled, cut into cubes and fed *ad libitum* to rats quite readily. If given to weanlings, renal cortical necrosis sometimes occurs. Given to rats aged 60-70 days, little interference with health is apparent other than poor weight gain and excessive greasiness of the fur. Addition of 100 mgm dried yeast per rat per week seemed to improve the animals' condition without reducing effectiveness in producing fatty liver.

Seven days on such a diet leads to fine fatty deposition in the liver, which gradually increases in extent and size of droplets to reach a maximum at about 20-30 days. After that time fibrosis develop in a proportion of animals (Fig. 9-5).
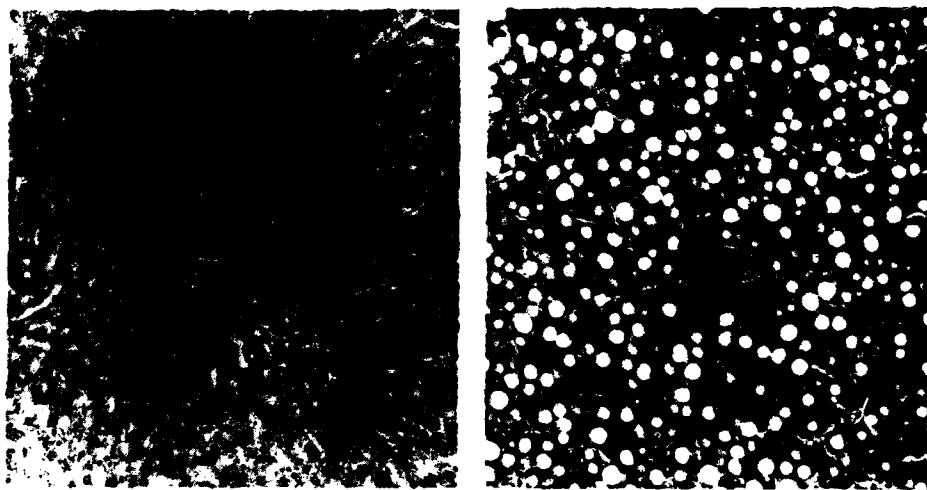
Fig. 9-5 (a) and (b) Sections of the livers of rats fed the Sutherland
high fat and high carbohydrate diet for periods of:
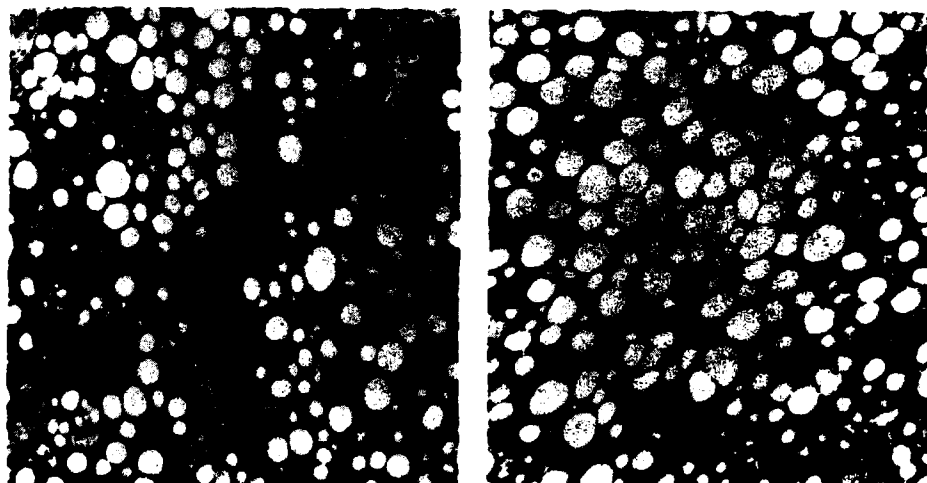(a) 7 days; (b) 13 days. H. & E. x 65.

Fig. 9-5 (c) and (d) Sections of the livers of rats fed the Sutherland
high fat and high carbohydrate diet for periods of:
(c) 30 days; (d) 43 days, H. & E. x 65.
Note that the liver in (c) is the site of developing
cirrhosis.

Histological and Experimental Techniques - As a standard procedure animals were killed with intra-peritoneal pentobarbitone. The lungs, ventricular portion of the heart, blocks of left and right lobes of the liver and both kidneys were bisected, half fixed in Zenker-formol and the other half in Formol-calcium. The whole brain was fixed in Formol-calcium. From Zenker-fixed material 6 μ paraffin sections were cut as follows: lung, left and right; liver left and right lobes; kidneys, left and right; heart. From Formol-calcium the tissues were embedded in gelatine and frozen sections cut on a freezing microtome at 15 μ. The brain was divided in the coronal plane into five blocks. Sections were stained by the writer's own modification of Wilson's stain, using Fettrot 7B in tricresyl phosphate as the fat stain and light green and haematoxylin as counterstains. Sections were examined as follows: lung, left and right, three of each; liver, two of each lobe; kidneys, left and right, two of each; heart, two; brain, three of each of five blocks.

Animals were treated in three groups - controls, hypoxic and high altitude.

a) Controls were kept in normal cages and culled at intervals.

b) Hypoxic animals were placed in a large perspex box through which a high flow of ventilating air was distributed by a gallery of perforated pipes (Gribble, 1954, had shown that with oxygen this technique, using the same regulator and box, maintained an oxygen concentration of some 98% at the altitudes used in these experiments). The animals were decompressed in $2\frac{1}{2}$ minutes to 14,000 feet, kept there for 1 hour and brought to ground level again over $2\frac{1}{2}$ minutes. Animals were killed subsequently at intervals up to 75 minutes after descent. The altitude of 14,000 feet was chosen on the basis of Gribble's extensive experiments in which he demonstrated that, on the basis of behaviour, for small rodents this altitude air-breathing represented an identical hypoxic stress to 40,000 feet breathing pure oxygen.

c) High altitude animals were treated exactly as were the hypoxic controls except that the final altitude was 40,000 feet and the ventilating gas oxygen.

Liver appearances

Visual grading as follows, has been adopted.

0 - no fat other than minimal dusting as in normal diet

$\pm$ - slight increase, fine droplets only

+ - mixed fine and coarse droplets affecting 50% of cells

++ - majority of cells fatty; 25% - 50% signet

+++ - more than 50% signet cells

(Signet cells being cells in which the fatty vacuole in paraffin sections is larger than the size of the normal non-fatty cell).

Results

Controls Groups

Most animals in this group were found to show no sign of fat embolism. The findings are shown in Table 9-3.

Table 9-3   Findings in control animals

Serial number	Days of diet	Age at death (days)	Weight change (gm)	Liver fat	Embolism
C1	7	168	+3	±	Nil
C2	13	35	-12	+	*
C3	16	39	-9.5	+	2 in lung section. 1 in kidney section
C4	17	178	-5	++	Nil
C5	20	40	-5.5	++	*
C6	24	88	+16	++	Nil
C7	24	88	N.R.	++	Nil
C8	24	88	+6	++	Nil
C9	24	88	+15	+++	Few - lungs only
C10	24	88	+4	+++	Few - lungs; 1 - kidney
C11	43	67	+24	+++	? inhaled fat
C12	43	204	+50	+++	? inhaled fat
C13	57	220	+47	+++	Nil
C14	70	133	-56	++	Few - lungs only; severe bronchiectasis
C15	84	246	-12	++	Several in lungs and glomeruli

* culled because ailing.   Found to have renal necrosis.

From these results it was concluded that pulmonary and systemic embolism were very uncommon except where fat feeding was prolonged. The appearances in the lungs of animals C11 and C12 were confusing, there being marked deposits of fat in alveoli and perivascular tissues. It is known that rats occasionally inhale particles of food, because one sometimes finds in sections of the lungs laminated bodies which are particles of bone-meal from crumbled pellets. It seemed improbable that the sticky, greasy cubes of the Sutherland diet could fragment in such a fashion as to give rise to intake by inhalation. However, when four animals were fed for sixty days on an identical diet to which fine carbon particles (carbon black) had been added during blending, unstained sections of the lungs showed clear evidence of carbon granules lining air passages and alveolar sacs (Fig. 9-6).

Armed with this knowledge one could be confident in rejecting clearly extravascular fat as not being displaced embolic material. However, lipaemic blood tends to stain and occasionally differentiation from true embolism is difficult. Trials on individual animals showed that reversion to a normal pelleted compound diet reduced the histological evidence of lipaemia without altering the hepatic appearances or causing embolism after one or two days; but that the liver cell picture changed when normal feeding was extended to four days. Consequently the experimental groups of animals were given pellets for thirty-six to forty-eight hours before decompression (see Tables 9-4 and 9-5).

Hypoxic Groups

In this series fourteen rats were used, in two batches of five and one of four. The animals behaved perfectly normally during the course of the one hour of hypoxia.

The results of examination of these animals are shown in Table 9-4.

The results of examination were the finding of minimal embolism in the lungs of three of the 34-day diet group, none of the 30-day group and all those fed the diet for 119 days. The latter group had evidence of fatty cyst formation and rupture with fibrosis some days before exposure to hypoxia. The presence of ceroid pigment in the lungs betrayed the chronicity of some of the fatty deposition.

Altitude Groups

In this series rats otherwise identically handled to the three sub groups of the hypoxic series were exposed to 40,000 feet for one hour. No behavioural changes were observed. Handling after exposure was identical to that of the hypoxic groups.

These animals showed no appreciable difference in the degree of embolism when compared with their hypoxic cage mates. (Table 9-5).

Summary of Animal Experiments

These trials showed that rats with fatty liver induced by a high-fat and high-carbohydrate diet suffered from little pulmonary fat embolism under normal cage conditions and had only slightly increased embolism of the lungs after exposure either to hypoxia or to high altitude decompression. There is no evidence that the 40,000 foot exposure resulted in greater release of fat than did the very mild iso-hypoxic 14,000 foot exposure and neither produced more than a very slight degree of embolism. The animals themselves showed no sign of distress. Thus it can be assumed that release of gas bubbles and cellular contents was minimal.

Fig. 9-6   Inhaled carbon particles in the lungs of rats fed carbon-black labelled Sutherland diet.   x 100 (upper) and x 200 (lower).

Table 9-4 Hypoxic groups of rats

Serial number	Days of diet*	Age at death (days)	Liver fat	Embolism
H1	34	109	+	A few in each lung
H2	34	109	+	NIL
H3	34	109	+++	Inhaled particles only
H4	34	109	+	2 or 3 true emboli in lung
H5	34	109	+++	A few equivocal in lung
H6	30	105	++	NIL
H7	30	105	+	NIL
H8	30	105	+++	Inhaled only
H9	30	105	++	NIL
H10	30	105	+	NIL
H11	119	142	++**	A few in lungs and glomeruli. Much inhaled.
H12	119	142	+++**	A few in right lung
H13	119	142	+++**	A few in lungs and glomeruli.
H14	119	142	+++**	Several in lungs only.

* H1-H10 re-fed pellets for 36 hours before exposure

*H11 to H14 re-fed pellets 48 hours.

* *H11-H14 all showed some hepatic fibrosis.

Table 9-5   Altitude groups of rats

Serial number	Days of diet*	Age at death (days)	Liver fat	Embolism
A1	34	109	++	A few in lung only
A2	34	109	+++	Several in lung only
A3	34	109	+++	A few in lung only
A4	34	109	++	A few in lung only
A5	34	109	++	A few in lung only
A6	30	105	+	Nil
A7	30	105	+	Nil
A8	30	105	+	Nil
A9	30	105	++	One in lung
A10	30	105	++	One equivocal in lung
A11	119	142	++**	A few in lung only
A12	119	142	+++**	A few in lung only
A13	119	142	+++**	Moderate numbers in lungs only
A14	119	142	++**	A few in lung only

* A1-A10 re-fed pellets 36 hours;   A11-A14 re-fed 48 hours
* * A11-A14 all showed hepatic fibrosis

225

Summary and Conclusions regarding Fat Embolism

Firstly, it is essential to recognise that fat embolism is not common to all fatal
altitude decompression sickness cases. Secondly, such fat embolism as has been
demonstrated is mainly pulmonary and slight in degree and therefore unlikely to be
of clinical significance. Thirdly, such systemic fat embolism as has been demon-
strated is so sparse as to represent an exceedingly improbable prime cause of ill-
ness.

Fat emboli are therefore relegated to a secondary role, as possible indicators of
disorder within fatty tissues. Among the latter the liver is the most probable
source. However, although there is considerable reason to suspect that fatty em-
boli originate in fatty livers, there is no indication from animal experiments to
support such liberation as a result of exposure to altitude.

Toxaemia and Bacteraemia

One of the most characteristic features of severe post-descent shock is the triad
of fever, leucocytosis and haemoconcentration. These could possibly result from
the passage of organisms or their products into the circulation.

The clinical picture given by circulating organisms of some types could account for
cases of post-descent shock. Good examples are some of the cold-growing bac-
teria which may contaminate stored blood (Bordon and Hall, 1951; Stevens et al,
1953) or other less common gram-negative organisms (Hall and Gold, 1955).

There has been much research on the role of E. coli endotoxin in shock of all kinds
and the evidence from animal work would certainly indicate the similarity between
the two conditions, although this far from proves their identity. Wangensteen, the
leading authority on intestinal obstruction, has pointed out the role of toxin absorp-
tion from the gut under such conditions (Wangensteen, 1955). Selkurt (1959) has
also shown the permeability to toxin of the anoxic gut wall and the vital part played
by the liver in detoxification.

Could it be that, at altitude, gut distension due to gas expansion causes absorption
of organism and toxins via blood or lymphatic channels, perhaps with deficient
hepatic detoxification in the presence of fatty change? The theory is attractive, but
falls down on several counts when critically considered. Gut distension is very
common in decompression procedures where rapid wide-range pressure drops are
produced, as in training of personnel in the use of oxygen equipment, and yet these
runs are remarkably innocuous. As will be discussed in Chapter 11, preoxygena-
tion is a remarkably effective preventive measure and yet it does not alter the in-
cidence of gut distension. Finally, and most cogent perhaps, is the fact that in
many cases of severe post-descent shock, including one fatal case, blood culture
has been performed, always with negative result. A toxaemic or bacteraemic
origin is thus presumably eliminated.

Endocrine Defect

The picture of the shock in the severe post-descent case bears a strong resemb-
lance to that seen in adrenal cortical suppression, either by disease as in the
Waterhouse-Friedrichsen syndrome or by artificially induced disturbance of the
pituitary-adrenal axis as in steroid therapy. It has often been suggested to the
writer that adrenal disease might underly susceptibility to the effects of decom-
pression. However, adrenal weight and histological appearances in all fatal cases
have been within normal limits. The only clue to any possible adrenal defect has
been in the case of diver's air embolism referred to earlier in this chapter. In
this man urinary steroid levels showed a remarkable lack of response to the severe

insult and Cooke interpreted that as a sign of possible adrenal gaseous embolism. It is hard to see how this could cause the profound changes seen in fatalities which occur within five to eight hours of ascent.

No evidence, therefore, exists to support a theory of endocrine defect as a cause of fatal reaction to altitude exposure.

Trapped Gas Barotrauma

An entirely new approach to the origin of gaseous embolism following decompression has arisen from the observations of Golding et al (1960) and the experiments briefly reported by Walder (1963). This has been the possibility that general or local elevation of intrapulmonary pressure could force gas into the pulmonary venous system and thence into the arterial blood stream.

The origin of this concept is in studies on submarine escape training in which men are required to leave a compartment in which ambient pressure has been raised to that of the surrounding water (33 feet of sea water being equivalent to one atmosphere) and ascend, with or without breathing apparatus, to the surface. In 1930 came the first, anonymous, report of a fatal collapse under such circumstances. The mechanism was baffling, because although the hall-marks of catastrophic decompression sickness were there, namely massive gaseous embolism, the trainee had ascended from 30 feet only, a depth universally accepted as completely safe with respect to decompression sickness. There followed other cases (MacClatchie, 1931; Brown, 1931; Adams, 1931), fatal and non-fatal. Polak and Adams (1932) and Behnke (1932) suggested that expansion of gas behind a closed glottis could have forced air into the circulation and Adams and Polak in 1933 convincingly demonstrated the validity of their theory in experiments on dogs. Adequate training and the substitution of free ascent techniques in place of the Momsen lung or Davis apparatus have reduced the casualty rate, although serious and fatal cases still occasionally occur (Kinsey, 1954; Thomason, 1957; Peirano, Alvis and Duffner, 1959). The mechanism was always regarded as voluntary breath-holding or glottal spasm due to fear or water entry into the laryngeal region. However, Liebow et al (1959) drew attention to an entirely new mechanism as a result of their investigation of two cases. In these they adduced evidence of obstruction of small segmental or lobular airways.

Golding et al (1960), apparently unaware of the work of the US Navy investigators, came to the conclusion that trapped gas might force itself into the circulation on the basis of their observations on two cases of decompression sickness in tunnel workers with pulmonary cysts. One of these took ten days to decompress from a little less than 3 atmospheres (absolute). Liebow et al (1959) had also observed cystic appearances in a chest radiograph of their non-fatal case and such pathology has been postulated as having been the cause of a compressed-air worker's death (Davidson, 1964A). However, care should be exercised in the interpretation of radio-graphs. For Collins (1962) has clearly demonstrated that in a US Navy non-fatal case cysts appeared as a result of, rather than as a cause of, intrapulmonary local gas trapping. Local or general pulmonary barotrauma, as this condition has become known, is a very major cause of injury and death in all aspects of underwater sport (Kruse, 1963; Denney and Glas, 1964; Denney and Read, 1965; Larn, 1965).

The mechanisms whereby air can leave the ruptured alveoli to enter the vessels of the lung, the interstitial planes and thence the mediastinum and occasionally, the pleural cavity, have been investigated by several workers (Malhotra and Wright, 1961 two papers; Schaefer et al, 1958).

Fahr in 1940 made a suggestion that not only might general obstruction arise at glottal level, but that emptying of alveoli might be impeded by narrow air passages at bronchiolar level. Walder (1963) showed very clearly that in guinea pigs with small airway constriction in general bronchospasm induced by histamine, decompression over a normally innocuous range can prove lethal and he tentatively advanced the theory that some caisson workers' symptoms might arise from such a mechanism.

Could such a pathology underly altitude cases? Benzinger (1950) has described apoplexy during intentional breath-holding during rapid decompression to simulate failure of an aircraft pressure cabin and clinical cases of pneumomediastinum and of presumed embolism have been reported in the literature (Clark, 1945; Holmstrom, 1958). The only recorded fatality is generally held to have resulted from deliberate breath-holding (Luft, 1954). No occurrences during decompression at normal ascent rates have been recorded as resulting from trapped gas and a retrospective survey of chest radiographs of severe and fatal cases of subatmospheric decompression sickness has shown no evidence of pulmonary air trapping. There is no necropsy evidence of such a mechanism and emphasis on this concept has waned since Bennison, Catton and Fryer (1965) failed in a very thorough search to find evidence of segmental lesions in a compressed-air fatality. The writer in a further unpublished case again could not demonstrate such an aetiology. The only active exponents of such a theory appear to be Hartmann and Wünsche (1961) who deduced from extreme altitude exposures of rats that bubbles were being introduced into the arterial blood stream from the alveoli. Their most convincing piece of evidence was the effectiveness in reducing the incidence of gas embolism of reduction of lung volume by pneumothorax or pneumoperitoneum. However, there is a distinct possibility that their experiments were complicated by violent convulsions in the rats and it is known that convulsions can be accompanied by very high intrapulmonary pressures. Also, their animals were exposed to an altitude (59,000 feet) at which additional pathological mechanisms arise which are not relevant to the classical human aviation case of decompression sickness.

Thus, although trapped gas barotrauma must be borne in mind, it does not appear either as sole or even major factor in the causation of death following altitude exposure.

Re-Appraisal and Summary

Few reviews of literature and experiments can have been more depressingly negative than this chapter. Is there no satisfactory explanation for post-descent shock?

The most striking fact is that the almost constant picture is one of haemoconcentration, fever and leucocytosis, preceded by signs and symptoms common in uncomplicated cases of decompression sickness and followed by a general progressive state of developing shock which is largely explainable on the basis of altered circulatory dynamics. The cause of the haemoconcentration is unknown, but in the absence of diuresis, extreme sweating or diarrhoea, an internal fluid loss must be postulated. Cotes (1953) has calculated that the pleural effusions and pulmonary oedema were not sufficient to account for the loss of circulating volume in the fatal case IX and examination of data from other deaths would support this view. In discussions on the proposal that general increase of capillary permeability might be responsible, it has often been argued that the absence of oedema makes such an explanation untenable. It must be realised that the whole of the body water could be transferred from compartment to compartment, intravascular, extracellular and intracellular, without any change in body mass or shape!

A loss of 3 litres of fluid into some 60 to 70 kilos of lean body mass would result in a rise in extravascular water concentration by some 5 per cent. When one considers that excised tissue contains a considerable quantity of intravascular material, it is not surprising that Cotes found the muscle and brain water levels in his case to be within normal limits.

What could cause such a general capillary leakiness? As has already been described, Cooke has found that accidental gaseous embolism can do so. Only recently has it become realised that the compressed air form of decompression sickness may also involve very severe haemoconcentration (Brunner, Frick and Buhlmann, 1964; Barnard et al. 1966). From the altered blood viscosity could arise the vascular changes *post hoc* rather than *propter hoc* as has often been suggested (Knisely, 1943; End, 1963; Robb, 1963; Elmino, 1965).

The mechanism whereby bubbles might produce vascular permeability changes remains obscure. Micro-trauma due to bubble formation may release vaso-active agents such as histamine, 5 hydroxy-tryptamine (serotonin) and active polypeptides or such materials may be liberated in loci where intravascular bubbles become impacted. The physiological and microscopical evidence for vasodilatation distal to bubbles would support the latter event (Duff, Greenfield and Whelan, 1953; Villaret and Cachera, 1939; Fleck, 1961). The very small final diameter of arterial bubbles would probably preclude their observation *post mortem*.

What of the origin of the bubbles? The fatty liver has been incriminated, but its meagre potential would appear to exonerate it as a major source. However, the prevalence of a fatty metamorphosis cannot be overlooked. Adipose tissue, in spite of the absence of tell-tale ecchymoses, would seem a very likely major source. A person overweight by 15 kg (34 lb) solely due to adiposity would be carrying 12.75 kg of extra fat, on the basis of an 85% fat composition of adipose tissue (Morse and Soeldner, 1965). A specific gravity of 0.93 would mean a volume of 13.66 litres for this mass and a solubility for nitrogen of 5.1 ml per 100 ml would allow this volume to contain 697 ml of nitrogen, some 70% more than in a lean person.

The excess obese tissue may have an influence on animal susceptibility has already been referred to and although altitude studies have been disappointing, those in compressed air have been very impressive (Antopol et al, 1964; Philp and Gowdy, 1964; Gowdy and Philp, 1965; Viotti and Walder, 1965).

This general hypothesis of bubbles from fat, disseminated throughout the circulation, causing increased capillary permeability is not without defects. Experimental evidence for release of enzymes and other active materials has not been obtained (Lalli and Paolucci, 1958; Kindwall, Boreus and Westerholm, 1962; Pecora et al, 1965). On the other hand, Chryssanthou et al have produced evidence that bradykinin antagonists may reduce the mortality among decompressed obese mice (Chryssanthou et al 1964).

Changes peculiar to a few of the altitude fatalities are hard to explain. Myocarditis, seen in two, could possibly be due to bubbles; Bing et al (1956) produced somewhat similar changes with plastic spheres of 300μ injected into coronary arteries, Harveyson, Hirschfeld and Tonge (1956) found multiple small myocardial infarcts in a case of air embolism in a diver and Spencer et al (1965) produced a histological picture of focal myocarditis in dogs into which a foaming mass of bubbles was introduced intra-arterially.

However complex or simple a theory one adopts, there is no apparent answer, however, to the greatest of all enigmas, the selectivity of the severe form of decompression sickness. Both in aviation and in compressed air work a man may

be exposed day after day to identical conditions before he suddenly and inexplicably succumbs. A high proportion of persons have a patent foramen ovale, and many aircrew have a fatty liver. Taking the incidence of the former at 20% and the latter at 20% (Mason, 1962) it would seem that about 4% of aircrew could be expected to have both conditions, each of which could be supposed, from post mortem evidence, to bring enhanced susceptibility to the effects of altitude. On what can depend the immunity both of the vast majority and of that 4% for the greater proportion of the occasions on which they are exposed? No explanation can be offered. Selective embolism of vital centres is a possibility, unsupported. Variable permeability of the pulmonary vascular bed can be invoked in cases with an intact atrial septum, but again without evidence.

It is to be hoped that improved therapeutic technique (see Chapter 11) will reduce the incidence of fatality. Thus, there is little hope of a break-through on structural evidence. Similarly, the effective treatment of severe cases will reduce chances of observation of changes in terms of clinical, biochemical and haematological study. It must be re-iterated that animal studies, useful as they are, are not as easily referred to findings in man as might have been suggested by some authors. Without going into detail, one aspect alone will serve as an example: the dog is very much more susceptible to decompression sickness after splenectomy and the mouse spleen showed fantastic 'Gruyère cheese' appearance in the experiments of Antopol et al (1964). The spleen in man, on the other hand, would appear to be inert in decompression sickness from such evidence as is found *post mortem*.

10

Differential Diagnosis

Introduction

It will be recalled that in the earlier part of this book it was stressed that the study of a disease must hinge on recognition of the condition and differentiation from all others. It is now apposite, after extensive consideration of the multifarious manifestations of decompression sickness, to discuss those conditions which may be encountered in the practice of aviation medicine wherein problems of differential diagnosis arise.

They naturally fall into three classes; those intercurrent illnesses which may coincidentally arise in association with flight, those physical and physiological disorders directly associated with flight at altitude and psychological reactions to such flight or laboratory simulation.

Intercurrent Illnesses

Flying does not offer any protection from intercurrent disease and therefore, on a purely chance basis, acute illness will occasionally arise during flight. The fact that no such case, diagnosed incorrectly as decompression sickness, has come to the writer's notice must reflect either the rarity of such events, their clear differentiation from decompression sickness, or both.

The most likely serious illnesses to mimic decompression sickness would appear to be those which give rise to chokes-like symptoms. Of these, myocardial ischaemia is most important, in that confusion could well arise between the constricting sensation and the inspiratory limitation of chokes and between anginal pain and bends in the left shoulder and arm. Whichever disorder is present, descent is imperative and differentiation must be a secondary consideration.

Spontaneous pneumothorax is a well recognised occurrence in young, apparently healthy flying personnel and a number of cases have occurred during flight. The pain and increasing breathlessness have never given rise to any diagnostic problems so far as differentiation from chokes is concerned.

Limb pains may arise from many causes, but the diagnosis of bends is so immediately apparent when pain eases or disappears during descent that , once more, practical problems never arise.

Physical and Physiological Flight Stresses

Pressure Vertigo

The construction of the Eustachian tube is such that inflation of the middle ear is

an active process, generally depending upon muscular activity to establish tubal patency; whereas deflation of the middle ear is normally passive. The result is that pressure imbalance is a problem during descent, giving rise to otitic barotrauma, whereas ascent is virtually totally without adverse effect.

However, on occasions there appears to occur some form of temporary impairment of outflow into the pharynx, characterised by sudden stimulation of the inner ear. The writer has twice experienced very acute vertigo and almost complete loss of balance during rapid ascent, accompanied by a 'plop' characteristic of opening of the mouth of the Eustachian tube. The sensation of disorientation is quite violent and like that induced by caloric testing of the inner ear. Lundgren first drew attention to this in the literature as a diving hazard in 1965, although it is certain that it was recognised among those working in this field long before this date. He coined the term 'Alternobaric vertigo' for this form of vestibular disturbance hitherto often called pressure vertigo and Lundgren and Malm (1966) found on interview that eleven of 108 pilots had experienced similar sensation during ascent and a further seven on descent or during the performance of the Valsalva manoeuvre.

Confusion with decompression sickness in compressed air workers and divers is possible, since a serious manifestation known colloquially as 'the staggers' begins with acute vertigo. It is, however, quite distinct from aviation forms of decompression sickness in its character and timing. Pressure effects of this type tend to occur at low altitudes where pressure changes are much more violent.

Abdominal Distension

In accordance with Boyle's law, contained gas expands in association with reduction of atmospheric pressure and the gas contained in hollow abdominal viscera is no exception. In some situations the attempt at expansion brings about a stretching of the visceral wall with pain and reflex muscular contraction. Thus small intestine and colonic gas can give rise to severe colic. As has already been stated, abdominal pain is a rare but serious symptom of decompression sickness. It may almost invariably be distinguished from simple gas pains as the Americans call gut distension, because true decompression sickness usually follows a symptom-free period, whereas gut distension arises during ascent.

The stomach, being a more capacious and distensible viscus may expand to a degree which is more liable to cause trouble from general abdominal tightness than from pain receptors in the visceral wall. A similar result may conceivably arise from expansion of multiple small loculi of gas throughout the alimentary canal. An example was seen in:

Case 23

> This young aircrew member was being decompressed to 37,000 feet at a rate of 3,000 feet per minute from ground level to 20,000 feet, 2,000 feet per minute from 20,000 to 30,000 feet and at 1,000 feet per minute thereafter. As the final altitude was approached he looked pale and complained of feeling faint. The writer, who was in the decompression chamber at the time, noticed that the person concerned was wearing trousers of a type which seem almost unique to British military uniform, namely tube-like and untapered from hips to a level just below the nipples.
>
> The victim was obviously experiencing abdominal discomfort due to distension and the trousers were clearly under considerable tension, for when the top few buttons were undone, the abdomen expanded, the faintness disappeared and the subject's colour returned. It is quite probable that, with such a corset-like garment in place, gas distension in the abdomen would be limited with resultant elevation of the

diaphragm and arise in intra-abdominal pressure. The latter could impair venous return from the lower limbs sufficiently to bring about syncope from blood-pooling.

A striking and apparently unique diagnostic exercise was provided by a case seen in 1962.

Case 24

A highly competent pilot, aged 32, was referred as a probable case of chokes. In 1954, he had experienced respiratory distress of unknown aetiology whilst flying at high altitude in an unpressurised trainer aircraft. a similar episode occurred in 1960. During the course of two decompression tests at 28,000 feet in 1960, he experienced mild bends.

Shortly before being referred to the writer he had been posted to a unit flying high performance reconnaissance aircraft and it was during a flight in such a machine that he experienced the distressing symptoms which led to his temporary suspension from flying. with a diagnosis of chokes. Whilst at a cabin altitude of 22,000 feet he developed a tight feeling in the chest. a burning sensation rising to the root of the neck and difficulty in speaking. He became soaked in sweat and found it difficult to swallow or to take a deep breath but experienced no inspiratory snatch. Descent to 15,000 feet cabin altitude made symptoms little better and even after landing he was conscious of a constriction in the throat and recurrent episodes as though "something kept welling-up into the throat".

The story sounded very like chokes. particularly in view of the proven susceptibility to bends. but there were odd features; the lack of inspiratory snatch, the absence of soreness on breathing, the absence of skin mottling and the failure of descent to 15,000 feet to relieve symptoms. The story was reminiscent of water-brash or oesophagitis and it was suggested that this pilot should be investigated to exclude hiatus hernia or any other oesophageal or gastric disorder.

In fact, radiological examination demonstrated a very lax and tortuous lower end of the oesophagus with almost a right angle between the distal end and the normal axis of the cardiac orifice. Tests carried out in a decompression chamber reproduced the symptoms exactly at an altitude of 15,000 feet, too low for serious consideration of decompression sickness. It is presumed that gas expansion in the stomach upon ascent caused distortion and possibly reflux of gastric contents into an abnormal lower oesophagus.

An employment category limiting this pilot to a cabin altitude of 12,000 feet was imposed and he had no further trouble until 3 years later, when he began to experience dyspeptic symptoms. unassociated with flying.

Hypoxia

In the mind of the average aircrew member, any disturbance of wellbeing occurring at altitude is first attributed to hypoxia and this is a correct response in many cases. It is essential that this attitude is maintained, for speedy correction of any oxygen fault is vital if consciousness is to be preserved. However, even when no faults are found and there is no response to a change of supply or an increase of oxygen flow, hypoxia is often still blamed.

In investigation of incidents in which the differential diagnosis between hypoxia and decompression sickness is difficult, certain features are of great value. For example, hypoxia to a degree where confusion is marked is almost invariably

followed by amnesia, so that a full and detailed account of symptoms is generally likely to support a diagnosis of decompression sickness. Visual disturbances in hypoxia are characteristically an apparent diminution in lighting intensity and tunnel vision. Neither is at all common in decompression sickness. Tremor is often conspicuous in hypoxia and unresponsiveness is very obvious to all around. In decompression sickness the victim is often acutely aware of all that is going on, manual dexterity usually suffers as a result of poor co-ordination rather than tremor.

Finally, in hypoxia, the reaction to restoration of oxygen supplies is vivid; vision becomes brighter, the victim becomes pink, co-ordination of eye and hand improve and suspended activity is replaced by feverish resumption of whatever task was on hand. Very occasionally restoration of oxygen results in a sudden worsening of condition with near or complete syncope, the so-called "oxygen paradox". In either event, the response to oxygen has no parallel in decompression sickness.

Motion Sickness

Some confusion may arise between motion sickness and decompression sickness. Sweating and pallor are common in both, but the stomach awareness, frank nausea and mental and physical wretchedness of motion sickness have a sequence and certain characteristics which have no equivalent in decompression sickness. Nausea without headache or severe abdominal pain for example, is rare in decompression sickness.

"Break-off Phenomenon"

Clark and Graybiel in 1957, described a phenomenon to which they gave the name 'break-off'. It can manifest itself in several ways but is basically a sensation of detachment and unreality, sometimes frightening, associated with flight at high altitude under conditions of low sensory input, relatively low physical activity and static environmental conditions. Under such circumstances people have delusions of being outside the aircraft, looking down on themselves, they lose sense of time and they feel that they have lost contact with the rest of the world. Susceptibility varies enormously but to those liable to the condition, flight at high altitude in a single seat pilot's compartment with a large transparent canopy and a continuous cloudscape below, can prove quite distressing and they have to be told to resort to such attention-arousing measures as listening to broadcasts, flying set patterns of manoeuvres, talking to other members of crew or persons in other aircraft or on the ground, etc. in order to prevent the onset of this strange sensation.

The sensation of impending doom which sometimes accompanies primary collapse in decompression sickness may be confused with break-off and vice-versa. More confusing is a history of repeated attacks of uneasiness in flight when one is attempting to elicit a history of minor attacks of decompression sickness. The principal point of importance is the relationship between flight conditions and symptoms. Association with poorly defined horizon, isolation within the cockpit and boredom would tend to suggest break-off as the origin of symptoms.

Acceleration Atelectasis

It is well established that pilots of high performance aircraft can experience basal segmental collapse as a result of certain in-flight manoeuvres. (Ernsting, 1960; Green and Burgess, 1962). The mechanism appears to be high perfusion and low ventilation of the lung bases under acceleration in the headward direction (+ve 'g') and absorption of gas from basal segments to the point of alveolar collapse (Glaister, 1965; Ernsting, 1965). The worst conditions appear to be a

combination of oxygen-breathing, acceleration and the use of an anti-g suit. The first leads to accelerated gas absorption, the second disturbs the ventilation:perfusion ratio and the third splints the rib-cage, limiting basal expansion.

The symptoms which originally drew attention to the condition are sharp pain and irritation on drawing a deep breath and paroxysmal coughing. The resemblance to chokes is, in the opinion of the writer who has experienced both syndromes, quite close. However, the history of the type of flight and the altitude at which it was performed, plus a characteristic onset at the time of vacating the aircraft, should enable the investigator to distinguish between this type of atelectasis and the chokes.

Psychological Stress

Fear

Straightforward fear reaction to high altitude flight, real or simulated, is rare, especially in aircrew. High pulse rates are often seen in inexperienced subjects of decompression chamber experiments, but with the exception of a few who never overcome their fears, familiarity soon leads to confidence.

Claustrophobia

Some subjects are distressed by the closed-in sensation of being in a decompression chamber. The writer has only once seen this reaction in a pilot. The diagnosis is clear in that the fear is expressed almost immediately upon entry.

Hyperventilation

Pulmonary ventilation beyond physiological demands is one of the commonest reactions to fear. In its grossest form it is quite obvious; a subject when placed in a decompression chamber, awed by the procedure, perhaps uneasy when using an oxygen mask, acutely conscious of his breathing by virtue of the noise emanation from the mask and regulator and amplified by the mask-mounted microphone, is seen and heard to breathe deeply and rapidly. As a consequence, the blood carbon dioxide tension falls and unless steps are taken to reduce CO_2 loss, the classical tingling, twitching, tetany and light-headedness of hypocapnia are seen.

Acute hypocapnia due to hyperventilation is often suspected as a cause of in-flight incidents, but proof is never found and the diagnosis is generally purely conjectural. Precipitating anxiety about some in-flight situation, acute awareness of breathing exertion, tingling in the extremities and light-headedness are the features which tend to support such a diagnosis.

However, much less well recognised and much more difficult to identify are the cases of slow-onset, sub-acute hypocapnia. Three examples seen by the writer are given since in each the differentiation between hyperventilation and decompression sickness was difficult and in fact, in two the possibility remains that both conditions were present.

Case 25

A 30 year-old medical officer agreed to act as observer during a routine decompression test of a pilot at 28,000 feet. The writer knew that this doctor had considerable experience of chamber work and was unaware of any past history of adverse reaction to altitude. Sixteen minutes after reaching altitude the medical officer complained of pain in his right hip and buttock and within 5 minutes of onset he elected to descend. The pain resolved completely.

About an hour after leaving the chamber, he complained of feeling light-headed, faint and extremely apprehensive. He lay on the floor, flushed, anxious and breathing very deeply and rapidly. He was carried to a couch and wrapped in blankets. Full examination revealed no abnormality other than the increased ventilation, tachycardia and a blood pressure of 175/95. He soon felt better but 10 minutes later he became acutely anxious, trembled violently, his face became very congested and he again breathed rapidly and deeply. He experienced several such attacks, each lasting 1 or 2 minutes. Between each he was very quiet. he became pale and he felt cold, shivering violently.

A pattern soon became established whereby he would suddenly say "I'm starting another attack", he would look panic-stricken, become flushed and he started to over-ventilate. Since the incident occurred in a respiratory laboratory, on-the-spot investigation was possible. In one attack he was found to be ventilating at 34 litres per minute and his end-tidal PCO_2 fell to 18 mmHg. At the height of a bout such as this he became very detached and unresponsive and was probably unconscious.

Over a period of $3\frac{1}{2}$ hours, during which time he experienced about 10 attacks, the symptoms gradually abated and finally he recovered but for a feeling of dull aching in his right cheek. Haematological investigation revealed no abnormality and urine chromatography showed no abnormal catecholamine output.

Subsequent enquiry revealed that this doctor had a history of at least three similar reactions following altitude exposure. In one he had abdominal distension and was observed to hyperventilate, in another he felt faint at 25,000 feet and on a third he exhibited a milder but extremely similar series of bouts of faintness, trembling and overbreathing. He clearly had a deep fear of such work and he reacted to abdominal gas-pains and on the last occasion, to bends pain, by paroxysmal hyperventilation. Each attack was heralded by acute fear, amounting to terror or *angor animi* and each seemed to leave him with a lower PCO_2, and thus more likely to feel unwell with resultant establishment of a vicious spiral of events.

Case 26

A 23 year old nursing officer was in the final phases of her training for casualty air-evacuation duties when she was admitted to hospital, having collapsed a few hours after a decompression chamber hypoxia demonstration. Decompression sickness was suspected but the subsequent events made that diagnosis less and less probable. The difficulty in reaching a firm diagnosis in the early stages was extreme, because adequate history-taking was impossible. In the light of enquiry after recovery was complete, the case clearly is closely parallel to that of the preceding Case 25. In reading the resume of the history it must be remembered that most of it was compiled after recovery.

One of the last events in the training course was wet dinghy drill in a swimming pool. The sister was far from fond of bathing and could not swim. She was anxious throughout but managed to complete the exercise, concealing her distaste for the procedure. Shortly after changing back into uniform she and her colleagues were driven in a coach to a decompression chamber, where they were taken to 25,000 feet and hypoxia was demonstrated. Again, this sister felt uneasy and she experienced abdominal distension. After leaving the decompression chamber she was observed to be very quiet and she developed a headache of steadily increasing severity.

After changing into civilian clothes the members of the course went out to celebrate at a local inn. Whilst chatting and consuming her first drink she became aware of generalised itching and tingling, tightness in the chest and faintness.

Consciousness became clouded or was lost and she collapsed. Her face muscles were observed to become stiff, her hands went into the classical position of carpopedal spasm and her respiratory rate fell to 8 per minute. She was taken to hospital where over the course of 5 days she had repeated attacks of the same kind. Usually as a response to stimulus, but once apparently in her sleep, she sighed deeply a few times, went into tetanic spasms, became very apprehensive and lost consciousness. She would remain apnoeic for a minute or so and then slowly recover. Haematological investigation revealed no abnormality and no clinical evidence of disease could be found. No neurological abnormality could be revealed but for a massive facial spasm in response to a tap over the facial nerve (Chvostek's sign). The plasma CO_2 level was measured at 22 mEq/L (normal 25-30).

Any attempt to raise the PCO_2 was frustrated, for any interference led to another attack of tetany. Rebreathing administration of 5% CO_2 in oxygen, increasing the dead space by breathing through a length of plastic hose, all failed because another attack was precipitated.

Finally on the fifth day the condition was arrested. Whether this was the result of administration of a mono-amine oxidase inhibitor (Stellazine) or a threat of forcible control of ventilation by use of a Drinker-type respirator will never be known.

Case 27

An aircrew officer aged 28 was being trained in the use of pressure breathing equipment and the final day of the course was to culminate in a rapid decompression to 56,000 feet, preceded by pre-oxygenation for 1 hour at ground level. In spite of clear instruction to the contrary, this young man and some of his colleagues consumed a large quantity of alcohol on the eve of this run. He had personal cause for tenseness and anxiety at this time.

In spite of the hang-over, the decompression was completed without any adverse reaction. Still anorexic and 'under the weather' he rested on his bed after the lunch break. About 3 hours after the chamber-run he noticed a fleeting impression of a dark patch in his visual field. Shortly after, whilst driving his car he became aware of a numb and weak feeling in both lower legs. He parked the car and boarded a train. He began to feel weak and faint and was conscious of palpitations. He counted his pulse and with difficulty calculated its rate to be 132/minute. He felt dizzy and on leaving the train 20 minutes later he sought aid from a railway employee. This proved difficult, partly because he found difficulty in constructing sentences, but mainly because of speech difficulty - his teeth were clenched and his jaw muscles contracted. He walked with a rather unsteady, broad-based gait to a nearby call-box and telephoned his unit for assistance. He returned to the station and lay on a seat, feeling tired, sweaty and noting that his hands were twitching.

On being placed in an ambulance he noticed difficulty with his breathing. He commented later that he tended not to breathe at all unless he made a conscious effort. He felt numb in all his extremities. Use of an oxygen administration set made him feel slightly better, presumably because he re-breathed from the reservoir bag. He was admitted to hospital, where no clinical abnormality was found and he had no set back to his recovery apart from a single brief feeling of anxiety.

Two days later he had an attack of itching, palpitations, anxiety and stiffness of the jaw muscles. He recovered spontaneously, but felt weak and tired for a week.

In each of these cases there is evidence of anxiety and apprehension. Each, it is postulated, over-ventilated quietly and inconspicuously during and after the exposure to altitude, partly from anxiety, partly as a response to discomfort (bends in Case 25 and abdominal distension Case 26). After an interval of 1-3 hours, the subjects became aware of the sensory disturbance due to the hypocapnia; tingling and numbness. The clenched jaw, twitching hands, tight chest are all felt to be part of this syndrome. There then followed episodes of paroxysmal overbreathing, disturbance of consciousness and tetany. In Case 26 even a few sighs appeared to be enough to tip the balance. In each episode, the body CO_2 level would be depleted and so each bout prepared the way for the next. The apprehension which heralds each successive episode is very striking and it may be triggered by very minor incidents. In discussion Case 27 acknowledged how he had responded to simple stimuli and incidental slight sensations which normally would pass without notice. To anyone who has had an illness which has premonitory signs, such as the aura of migraine, the sudden pain which heralds exacerbation of a prolapsed intervertebral disc, the unease which precedes a faint, this feeling of "here we go again" has true meaning.

Diagnosis is not difficult *post hoc* but it was far from easy at the time. The lessons to be learned are that acute clinical observation of these attacks should give the clue to the diagnosis: sudden anxiety, hyperventilation, carpopedal spasm, tachycardia, and then hypopnoea or apnoea are typical. The PCO_2 level found in Case 25 reveals clearly how insidious can be the hyperventilation leading to this state: this doctor was surrounded by experienced respiratory physiologists from the time that he left the decompression chamber until his first acute attack of distress.

The hidden danger in the recognition of this syndrome is that it might one day occur in a person genuinely entering a state of post-descent shock. It is strongly recommended that estimation of PCV and white cell count should be made routinely even when the diagnosis of hyperventilation appears clear.

Misdiagnosis

Detailed knowledge of decompression sickness is not widespread and it is an ever-present danger that a severe case of decompression sickness will be made worse or may even succumb through misdiagnosis.

Many an aircrew member has sat through bends, chokes or visual disturbance, blaming his symptoms on cold, cramp, hypoxia or 'flu. Education and maintenance of awareness is the only possible solution.

Occasionally cases have been misdiagnosed due to lack of knowledge on the part of the doctor. For example, a clinician faced with an unconscious pilot, mottled, febrile, complaining of headache and nausea, is likely, quite reasonably, to diagnose septicaemia. This occurred in the case of one British fatality. Even when the doctor is trained and aware of the hazards of high altitude flight, he may be misled through lack of relevant information. The example has already been quoted in Case 18 where a doctor diagnosed the prevalent virus infection because he was unaware that his patient had been decompressed earlier that day. Awareness of the hazards of altitude must be instilled into those exposed and their medical advisers.

Spurious Complaints

A proportion of claimed symptoms undoubtedly are spurious. Many reasons may underly falsification; apprehension of the unknown, fear of recurrence of previously

experienced symptoms, a desire to be withdrawn from flying duties and exaggeration of minimal discomfort. Suspicion of such cases may be aroused in many ways, by the demeanour of th patient, the nature of the complaint, the circumstances of the occurrence and the reaction to the incident.

When doubt exists it is generally wise to carry out a test, of a type known as a 'foxing' run. It has been found that the following plan is most effective:

Suppose the subject claims to have experienced strange symptoms at the very low altitude of 20,000 feet. In the morning of the examination he is told that he will be exposed to an altitude at which he believes himself to be prone to develop symptoms, 25,000 feet, but in fact he is taken only to 15,000 feet. If he reports symptoms, the complaint is virtually proven to be false. After as long an interval as is reasonable a second run is commenced. This time the subject is told that he will be tested for a longer period but at a lower altitude,20,000 feet. In fact, he is exposed to a simulated altitude of 35,000 feet. If on both occasions he claims to be symptom-free, it can be explained that his previous episode was probably imaginary and he can be sent away, reassured. If he experiences pain on the second run only, the ruse of the test may be revealed and he may be again assured that his reaction which led to his examination was probably an isolated incident. If, however, having complained of symptoms on the first occasion, a clear run is recorded on the second, grave suspicion is aroused that the subject is either betraying some anxiety by imagination of altitude sensitivity, or is deliberately falsifying.

Summary

An incorrect diagnosis of decompression sickness may be a serious error, in that an aviator's career may be jeopardised. A number of conditions may mimic the pain of bends or chokes and other reactions to altitude may result in misleading suspicion of decompression sickness. Very serious indeed may be the outcome of failure to recognise decompression sickness, since the progress of post-descent shock is so relentless that speedy treatment is essential. The greatest difficulty arises in cases where a psychological overlay, often reflected in hyperventilation, makes an otherwise minor incident into a major illness.

11

Treatment

Introduction

It is hardly surprising that treatment of cases of severe decompression sickness has, on the whole, been of limited success. The histories of published cases in large series, such as that of Adler (1950), record little, if any difference in initial severity, character or treatment between survivors and fatalities. Treatment can really only be based on two principles; the alleviation of symptoms and the elimination of the cause. From Chapter 9 has emerged a dismal picture of our knowledge of the cause and therefore treatment has, until comparatively recently, been of the first type, namely aimed at symptom relief.

General Measures

In this category come those measures aimed at the relief of the clinical manifestation as witnessed at the bedside. It includes fluid replacement, oxygen, stimulants and steroids.

Fluid Replacement

Since the early 1940's when the role of haemoconcentration first became apparent, replacement of lost circulating volume has been the recommended prime treatment of severe decompression sickness resulting from altitude exposure. However, in spite of successful recovery of cases after infusion of up to ten pints of fluid, many authors of case reports seem to have been unaware of the recommendation and doubtless recovery has at least been delayed.

The aim must be restoration of a normal haematocrit value without circulatory overloading and consequent pulmonary oedema. For this purpose either plasma or a plasma-expander like dextran will appear to be a better choice than saline or dextrose.

Malette, Fitzgerald and Cockett in 1961 reviewed much of the literature, citing thirty-five cases previously published elsewhere. Two of the authors have, with collaborators, pursued the concept of fluid replacement relentlessly on the basis of high-pressure decompression sickness or high-to-subatmospheric decompression sickness in splenectomised dogs (Cockett, Nakamura and Franks, 1963A; 1963B; Cockett and Nakamura, 1963; Cockett, Nakamura and Kado, 1965, Cockett and Nakamura, 1965).

In compressed-air work and diving, recognition of haemoconcentration has been much slower and only recently has the need for fluid replacement been acknowledged as a vital part of therapy. This particularly applies to the stubborn case which responds poorly to recompression (Cockett and Nakamura, 1964; Brunner, Frick and Bühlmann, 1964; Barnard et al, 1966).

The essence of this form of treatment must be early and adequate infusion, guided by serial haematocrit readings and observation of the circulation for evidence of overloading, preferably by measurement of the central venous pressure.

Very rapid haemodilution is also achieved by the use of mannitol infusions and this agent may well find an established place for the early revisal of haemoconcentration.

Somewhat apart from the general trend of observations in this field is the report by Pallotta (1963) of remarkable improvement with administration to severely ill human cases of high-pressure decompression sickness of as little as 250 ml of plasma.

Oxygen

Cyanosis is generally present in cases of post-descent shock, although in surprisingly few cases has differentiation been made between central and peripheral cyanosis. This condition is presumably due to sluggishness of the circulation resulting from the haemoconcentration and peripheral vasoconstriction and possibly also to apparent veno-arterial shunting of blood in the lungs when ventilation of some segments is deficient.

There can be no doubt that oxygen administration is to be recommended in the presence of cyanosis.

Stimulants etc.

When cardiac or respiratory arrest threatens, stimulants such as nikethamide may help to improve the patient's condition temporarily, but their effect is generally transient and they must be supplemented by fluid replacement, oxygen and other measures as indicated.

Although not strictly in the category of stimulants, certain vasoconstrictor drugs, which often have in addition stimulant properties, may be considered here. In their turn amphetamine, methylamphetamine, nor-adrenaline and aramine have been used. Two quite fundamental facts seem to indicate the underlying reason for their apparent ineffectiveness in this form of shock; firstly, hypotension is almost invariably a late or terminal event and secondly, it is apparent in these cases that peripheral vaso-constriction is very marked at an early stage. In the severe case, in which the vaso-constriction may be so severe that the radial pulse is impalpable although the brachial artery pressure is normal, and in which blood viscosity must be enormously raised by haemoconcentration, it would seem fundamentally erroneous to administer vaso-constrictor drugs.

Steroids

It has been fashionable for many years to administer steroids to cases of shock. The rationale is much less well known than is generally acknowledged (Shoemaker, 1967). Very dramatic results have been reported in many forms of shock, particularly where over-whelming infection is present (Kinsell and Kahn, 1955), when adrenal cortical tissue is deficient or when adrenal cortical activity has been depressed by administration of steroids. When none of these conditions is present, the administration appears to be on a less sound scientific basis (Abbot, Krieger and Levey, 1955) but nevertheless it is common practice to give large doses of

Prednisone or Prednisolone orally, or a soluble form of steroid, such as hydro-
cortisone hemisuccinate, intravenously. This would appear to be without danger
as a single dose and provides an excellent insurance policy against undiagnosed
depressed adrenal function.

Other General Measures

Circumstances may demand the use of other drugs, such as paraldehyde in hyper-
excitable states, antihistamines in the presence of urticaria and analgesics in cases
experiencing severe abdominal pain. The latter drugs should be chosen with
care, as respiratory depression by morphine or morphine-like drugs is contra-
indicated by central cyanosis.

It is now well established that many forms of shock respond well to hypothermia,
induced by exposure or active cooling, chlorpromazine, pethidine and phenergan
(the so-called "lytic cocktail"). A single case of "aeroembolism" so-treated with
success is recorded in the aviation medicine literature (Bauer et al, 1965), but
rather misleadingly, for the condition was induced not by ascent, as would be
suggested by the name given to the condition, but during abortion by uterine insuff-
lation.

Treatment of Fat Embolism

On the assumption that fat embolism plays a major role, many therapeutic meas-
ures have been advocated for use in decompression sickness. One of the most
popular drugs is heparin. On the basis of its well-established lipaemia-clearing
property it is supposed that its use will inhibit coalescence of chylomicra in the
blood. Laborit, Barthélémy and Perrimond-Trouchet (1961) reported striking
protection of experimental animals and successful use in a human case of para-
plegia from high-pressure decompression sickness. However, in the animals
pre-treatment seemed essential. Many clinical claims of success with heparin
in proven fat embolism have nevertheless appeared in the literature (Freeman,
1962) and equally, counter-claims of danger in the form of provocation of haemor-
rhage have been made (Harrison, 1962).

Much more closely related to the therapy of decompression sickness is the work
of Philp (1964) and Gowdey and Philp (1965) who protected lean rats against
decompression death by use of partially depolymerized hyaluronic acid (PDHA),
a heparin analogue with lipaemia-clearing but no anticoagulant properties.

Use of heparin or its analogues in human decompression sickness would appear to
be limited to the single case of Laborit, Barthélémy and Perrimond-Trouchet.
In the light of the frequency of capillary haer orrhage into the lungs, the stomach
wall and the mesentery, it would seem to be a rather hazardous procedure to be
reserved for desperate circumstances.

Another approach, only reported from animal experiments, is the use of surface-
active agents (Adams et al, 1959).

The most generally adopted treatment for fat embolism is hypothermia (Harnett
et al, 1959; Aladjemoff et al, 1963; Hamilton, 1964). A possible mechanism
responsible for apparent success is elevation of fat viscosity, preventing systemic
dissemination (Illingworth, 1967), but the general response of any form of shock
to hypothermia is such that the postulation of mechanisms is perhaps somewhat
academic.

Treatment of Air Embolism

Massive air embolism has been successfully treated by many methods, but those
which are recommended for use in such emergencies, as are encountered in
surgery, are aimed primarily at the relief of cardiac embarrassment by foam
blockage of the right heart. As such they are of less potential value in conditions
where small bubbles are believed to be arriving almost continuously in the pulmo-
nary circuit. However, it is worth taking notice of the effective manoeuvres,
particularly if one is contemplating the treatment of emergencies with minimal
facilities or cases of suspected trapped gas barotrauma. The "Durant manoeuvre"
of placing the patient on his left side, head down appears to reduce circulatory
disturbances by channelling bubbles into the atrial appendage rather than the pulmo-
nary conus (Nicholson and Crehan, 1956). In mixed arterial and venous air emb-
olism, head-down tilt appears to be of value also (Atkinson, 1963). When cardiac
arrest occurs, closed chest massage may help to restore heart action (Ericsson,
Goltlieb and Sweet, 1964).

Several papers have been published in which it is claimed that drugs may influence
the outcome of decompression or of experimental gaseous embolism. Malette,
Fitzgerald and Eisman (1960) reduced the mortality among rats subjected to very
rapid decompression from ground level to 71,000 feet by pre-treatment with an
anti-foam, methylsiloxane, presumably by altering the surface tension of the blood.
Lyle and Fitzgerald (1961) gave procaine intra-arterially via the carotids before
introducing air by the same route. They claimed that the resultant reduction in
mortality compared with control animals, was associated with prevention of vascular
spasm, ignoring the evidence of Villaret and Cachera (1939) that spasm does not,
in fact, occur in these vessels as a response to gas embolism. Furry (1964) found
a protective effect for lignocaine given to rats prior to explosive decompression,
but his experiments are complicated by pre-decompression vibration of the rats as
an additional stress.

Compression Therapy

The most obvious way of reducing the effect of bubbles is to reduce their volume.
This may be achieved by absorption, compression or a combination of both. Over-
compression has long been the therapeutic measure for difficult cases of compre-
ssed-air workers' or divers' decompression sickness, although occasionally field-
workers express preference for recompression until relief as a rule for therapy
(Gerbis and Koenig, 1939; Griffiths, 1959).

Restoration of an aviator to ground level is equivalent to recompression of a com-
pressed air worker to working-pressure and as such is to be expected to be highly
effective. However, if bubbles persist after descent, further compression may
be expected to aid their disappearance. The physiological conditions at the bubble/
tissue interface are complex because at the same time as the bubble is compressed,
gas tension is rising in surrounding tissues and fluids. Bubble disappearance can
only be expected to occur as a prompt result if compression reduces the volume
such that the forces of surface tension overcome tension gradient across the inter-
face, that is when bubbles become sub-critical in size. Much more important in
practice is the effect of compression reducing bubble diameter, allowing centrifugal
disposal, within the circulation. Here it must be remembered that pressure is
related directly to 1/volume at constant temperature (Boyle's law) but that diameter
is a function of the cube root of the volume and that, therefore, large pressure
changes produce relatively small diameter changes.

For many years in the post-war period there was discussion between workers in the
aeromedical field about the advisability and possible effectiveness of over-pressure

treatment of altitude decompression sickness. Plans existed for a recompression chamber at Farnborough and consideration had been given to the best regime for therapy. The prospect of success would seem, at that time, to have been somewhat dubious. There was no convincing evidence for bubbles in man in subatmospheric conditions, there was little reason to suspect that bubbles even if they existed could persist after descent and the experimental evidence suggested that compression would have to be commenced within a matter of minutes of the onset of symptoms. Lutz (1953) had demonstrated this time factor very convincingly in experiments on dogs given air intravenously.

Planning was difficult; if a facility was made available, how should it be used? If relatively mild cases were to be treated, how would efficacy be judged, since the great majority recover spontaneously? An ideal would be treatment of alternate cases, but who could withhold the chance of over-pressure treatment from a really sick patient?

Unknown at the time was the fact that in 1941 a doctor had had persistent limb pain treated successfully at 44.5 lb/sq. in. (gauge, see Note, page 257) (Goodman, 1964)

The first published case was that of Donnell and Norton (1960). At one blow it solved one of the fundamental problems of altitude physiology and it established without doubt the value of high pressure therapy, even after a long delay. Briefly, a 39 year old aviator, during the course of a training procedure which involved pressure breathing, hypoxia and rapid decompression, developed weakness and paraesthesiae of the left arm and mild chokes. After descent he recovered somewhat, only to develop headache, nausea, vomiting and confusion and weakness of his arm recurred. The only feature atypical of post-descent shock was a normal packed cell volume. Within less than five hours he was moribund and it may be stated with near-certainty that under conventional treatment he would have died. However, with great good fortune, the Command Surgeon, a doctor with a very long-standing interest in decompression sickness, recommended use of a recompression chamber at a nearby naval base.

Almost six and a half hours after the initial symptoms developed the patient was compressed to 6 atmospheres absolute. There was dramatic improvement of cardio-vascular status and slow recovery of the weakness and confusion. The standard treatment, the USN Therapeutic Table 4 was followed, with a total compression time of thirty-eight hours. The end result according to the review by Goodman (1964) was "subtle neurological deficits and a neuro-psychological dysphasia". It is hard to imagine a more striking piece of evidence for the role of bubbles in decompression sickness arising at altitude and the efficacy of compression after a long delay was quite remarkable.

In the next year, 1961, a second case of successful therapy was reported by the USAF (Bratt, 1961; Berry and Smith, 1962). A photographer developed severe bends, weakness and chokes after the aircraft in which he was flying suffered a pressurisation failure. He almost completely recovered on descent, but after a brief lucid interval he developed severe shock. Recompression six hours after onset brought potential relief at 3 atmospheres absolute and complete recovery after full Table 4 treatment to 6 atmospheres.

Coburn et al in 1962 reported on the first British case so treated and they recorded success after a modified regime with a maximum pressure of 3 atmospheres absolute. Cannon and Gould (1964) described this case again, together with three further Royal Navy cases, all treated at 3 to 4 atmospheres absolute.

Stops	Bends-Pain only	
Rate of descent 25 ft. per min. Rate of ascent- 1 minute between stops.	Pain relieved at depths less than 66 ft. Use table 1-A if O_2 is not available.	Pain relieved at depths greater than 66 ft. Use table 2-A if O_2 is not available. If pain does not improve within 30 min. at 165 ft. the case is probably not bends. Decompress on table 2 or 2-A.

Pounds	Feet	Table 1	Table 1-A	Table 2	Table 2-A
73.4	165	-----	----------	30 (air)	30 (air)
62.3	140	-----	----------	12 (air)	12 (air)
53.4	120	-----	----------	12 (air)	12 (air)
44.5	100	30 (air)	30 (air)	12 (air)	12 (air)
35.6	80	12 (air)	12 (air)	12 (air)	12 (air)
26.7	60	30 (O_2)	30 (air)	30 (O_2)	30 (air)
22.3	50	30 (O_2)	30 (air)	30 (O_2)	30 (air)
17.8	40	30 (O_2)	30 (air)	30 (O_2)	30 (air)
13.4	30	5 (O_2)	60 (air)	60 (O_2)	2 hrs. (air)
8.9	20		60 (air)	5 (O_2)	2 hrs. (air)
4.5	10		2 hrs. (air)		4 hrs. (air)
Surface			1 min. (air)		1 min. (air)

Time at all stops in minutes unless otherwise indicated.

Fig. 11-1.   U.S.N. Therapeutic Tables (from US Navy Diving Manual).

Serious Symptoms

Serious symptoms include any one of the following:

1. Unconsciousness.
2. Conculsions.
3. Weakness or inability to use arms or legs.
4. Air embolism.
5. Any visual disturbances.
6. Dizziness.
7. Loss of speech or hearing.
8. Severe shortness of breath or chokes.
9. Bends occurring while still under pressure.

Symptoms relieved within 30 minutes at 165 ft.	Symptoms not relieved within 30 minutes at 165 ft.
Use table 3	Use table 4

Table 3	Table 4
30 (air)	30 to 120 (air)
12 (air)	30 (air)
12 (air)	30 (air)
12 (air)	30 (air)
12 (air)	30 (air)
30 (O_2) or (air)	6 hrs. (air)
30 (O_2) or (air)	6 hrs. (air)
30 (O_2) or (air)	6 hrs. (air)
12 hrs. (air)	First 11 hrs. (air) Then 1 hr. (O_2) or (air)
2 hrs. (air)	First 1 hr. (air) Then 1 hr. (O_2) or (air)
2 hrs. (air)	First 1 hr. (air) Then 1 hr. (O_2) or (air)
1 min. (air)	1 min. (O_2)

Time at all stops in minutes unless otherwise indicated.

Fig. 11-1. U.S.N. Therapeutic Tables (from US Navy Diving Manual).

Goodman (1964) performed a most valuable function when he collected together these six published cases and eight others. He found that twelve had experienced permanent relief and that the remaining two had mild CNS residua.

The value of recompression or over-pressure therapy is quite beyond doubt, but there have developed three schools of thought with regard to the best regime to be adopted.

The original trend shown for the treatment of really severe cases was that of the US Navy Tables 2, 3 or 4 (see Fig. 11-1), involving pressurisation of up to 6 atmospheres absolute (165 feet) and decompression of ten to forty-five hours (Goodman's cases 4, 5, 6, 8 and 9). The rationale to these tables is largely based upon a compromise between maximum pressure and the avoidance of serious levels of nitrogen narcosis. The depth of 165 ft is such as to bring about bubble size reduction by about 50% (USN Diving Manual, 1963).

A second school favours limitation of pressure to that at which relief is first clearly established (Cannon and Gould, 1964). The reduced recompression times are obviously much more convenient and it is rational and reasonable to postulate that, at a level where relief is felt, the bubbles are reduced to a non-traumatic size. Most cogent of all is the suggestion that at high pressures, if a bubble has not disappeared, gas will diffuse into the pre-formed nidus during decompression and one has converted a subatmospheric case to compressed-air case.

The third and most recent trend has been that led by Workman and Goodman in the United States. On most excellent theoretical grounds they can demonstrate quite conclusively that oxygen breathing, particularly at raised pressure, creates the most favourable condition for removal of inert gas from bubbles. A typical early schedule is shown in Figure 11-2.

To understand the theoretical background it is necessary to consider the tension gradients across a bubble wall. Imbalance between tension of any components of a gas mixture in solution and in a bubble will lead to diffusion and equilibration. Thus, in an air-breathing animal bubbles of oxygen and of nitrogen introduced as pure gases should theoretically equilibrate in time each to contain a mixture of gases, the tension of each component equal to the tension in the surrounding tissue. If the total pressure of gas in the surrounding fluid (i.e. the sum of partial pressures, including that of water vapour) is equal to that of the surrounding atmosphere, the bubble will theoretically remain the same size indefinitely. This situation will apply in proximal parts of arteries, but not in any part where metabolism has occurred, for even where R (the ratio of O_2 utilisation to CO_2 production) is 1, equal volumes of O_2 and CO_2 exert quite disproportionate tensions because of their different solubilities and therefore the sum of partial pressures of gases will not equal 1 atmosphere. For example, in arterial blood leaving alveoli one may assume blood gas tensions to be in, mmHg:-

(Using normal abbreviations of respiratory physiology; P = partial pressure, subscript a = arterial, A = alveolar and V = venous.)

$$P_aO_2 \quad = \quad 100$$

$$P_aCO_2 \quad = \quad 40$$

$$P_aH_2O \quad = \quad 47$$

$$P_aN_2 \quad = \quad 573$$

$$P_B \quad = \quad \overline{760}$$

Depth-time parameters for minimal compression-oxygen breathing therapeutic profile

Treatment phase	Depth (ft)	Time (min)	Total time (min)	Gas	Remarks
Compression	0-60	2	2	oxygen	rate variable
Test of relief	60	10	12	oxygen	must be complete
Relief complete	60	26	38	oxygen	use Table B if
within 10 min.	60	2	40	air	symptoms persist
Ascent to 33	60-58	2	42	air	uniform ascent,
feet	58-33	225	67	oxygen	1 FPM
One atm. abs.	33	30	97	oxygen	uninterrupted
Final ascent	33-0	33	130	oxygen	uniform ascent, 1 FPM

Method for persisting symptoms for maximal, safe tissue reoxygenation

Compression	0-60	2	2	oxygen	rate variable
Breathing mixture	60	28	30	oxygen	interspersed air
alternation pat-	60	15	45	air	breathing pro-
tern for 60 ft.	60	28	73	oxygen	longs OHP pre-
exposure	60	2	75	air	convulsive latency
Ascent to 33	60-58	2	77	air	uniform ascent.
feet	58-33	25	102	oxygen	1 FPM
Breathing mixture	33	15	117	air	interspersed air
alternation pat-	33	60	177	oxygen	periods for com-
tern for 33 ft.	33	15	192	air	fort; (attendants
exposure	33	60	252	oxygen	on air entire 285 min)
Final ascent	33-0	33	285	oxygen	uniform ascent, 1 FPM

Fig. 11-2   Minimum-Pressure plus Oxygen-Breathing Therapeutic Schedules (Goodman, 1964).   Reproduced by permission of the Aerospace Medical Association.

whereas in venous blood, PO_2 having fallen by a much greater degree than PCO_2 has risen,

$P_V O_2$	=	40
$P_V CO_2$	=	45
$P_V H_2 O$	=	47
$P_V N_2$	=	573
P_V Total =		705

The resulting inherent unsaturation, to the extent of 760-705 = 55 mmHg, means that any introduced pocket of gas in contact with such a medium will tend towards a composition of O_2, CO_2, H_2O and N_2 in the ratio 40:45:47:573. This will mean a ΔPN_2 across the pocket or bubble wall tending to cause diffusion outwards and the gradual absorption of the gas since equilibrium is never reached, $P_V N_2$ being held almost constant by replenishment with arterial blood with a PN_2 of 573.

Experimentally, a negative pressure relative to ambient can be demonstrated to develop in gas-filled capsules embedded in animals (Guyton, 1963; Le Messurier and Hills, 1966; Hills, 1966) and the dynamics of the process of gas absorption have been particularly elegantly investigated both theoretically and experimentally by Van Liew (1962).

Compression of an enclosed gas pocket or bubble results in a very complex sequence of gas exchanges, since CO_2 diffuses outwards more rapidly than does O_2, but Van Liew et al (1963) have shown how to calculate the conditions which exist between the time of initial equilibration and final absorption. Fundamentally, the ΔPN_2 across the interface will be equal to the sum of the tension differences of O_2 and CO_2 between pocket and surrounding medium.

For example, at 6 atmospheres absolute, alveolar CO_2 and H_2O tensions remaining constant at 40 and 47 mmHg respectively, the alveolar and thus the arterial PO_2 and PN_2 may be calculated by use of the alveolar air equation (Comroe et al, 1962):

$$P_A O_2 = F_{IO_2} (P_B - PH_2 O) - P_A CO_2 \left[F_{IO_2} + \frac{1 - F_{IO_2}}{R} \right] \times F_{IO_2}$$

Where:

F_{IO_2}	=	fractional concentration of oxygen in dry inspired gas
P_B	=	atmospheric pressure
$PH_2 O$	=	water vapour pressure at body temperature
$P_A CO_2$	=	alveolar partial pressure of CO_2
R	=	respiratory exchange ratio

Using an assumed R of 0.8, substituting, one may obtain:

$$P_A O_2 \quad = \quad (0.2093 \times 4513) - (40 \times 1.2)$$

$$\therefore \quad P_A O_2 \quad = \quad 944.5 - 48$$

$$\therefore \quad P_A O_2 \quad = \quad 896.5 \text{ mmHg}$$

Since, in the lungs, the total atmospheric pressure must be equal to the sum of the tensions of the component gases O_2, CO_2, H_2O and N_2, we may calculate $P_A N_2$ as follows:

$$P_A N_2 \quad = \quad P_B - (P_A O_2 + P_A H_2 O + P_A CO_2)$$

$$\therefore \quad P_A N_2 \quad = \quad 4580 - 983.5 = 3576.5 \text{ mmHg}$$

Assuming unaltered blood flow and oxygen utilisation as in the 1 atmosphere case, the venous gas tensions air-breathing at 6 atmospheres may be calculated. Allowing 36.5 mmHg for the alveolar-arterial oxygen difference (a reasonable assumption at such a high $P_I O_2$) and -3.5 mmHg for the alveolar-arterial N_2 difference (Cotes, 1965), we may derive arterial gas tension of:

$$P_a O_2 \quad = \quad 860$$

$$P_a CO_2 \quad = \quad 40$$

$$P_a H_2 O \quad = \quad 47$$

$$P_a N_2 \quad = \quad 3580$$

In the previous 1 atmosphere example, the oxygen utilisation may be calculated from a knowledge of tensions, the dissociation curve for HbO_2 and the Rahn and Fenn $O_2:CO_2$ diagram (Comroe et al, 1962). The arterial blood in the 1 atmosphere case would be 97.5% saturated and at 20.6 ml O_2 per 100 ml whole blood HbO_2 and a solubility of 0.003 ml/100 ml blood/mmHg P_{O_2}, the O_2 content would be 20.08 + 0.3 = 20.38 ml O_2/100 ml.

The venous blood content, from similar calculations would be 16.72 ml O_2/100 ml and the oxygen extraction in the tissues 4.11 ml O_2/100 ml blood.

In the 6 atmosphere case of air breathing the arterial O_2 would be 23.18 ml O_2/100 ml and a similar extraction rate would give 19.07 ml O_2/100 ml venous blood, corresponding to a $P_V O_2$ of 65 mmHg.

Thus we may calculate venous tensions of:

$$P_V O_2 \quad = \quad 65$$

$$P_V CO_2 \quad = \quad 45$$

$$P_V H_2 O \quad = \quad 47$$

$$P_V N_2 \quad = \quad 3580$$

$$\underline{}$$

$$= \quad 3737 \text{ mmHg}$$

(Total venous gas tension)

The inherent unsaturation has thus risen to 4560 - 3737 = 723 mmHg, compared with 55 mmHg at 1 atmosphere, a 13-fold increase in driving pressure for gas removal from bubbles.

However, as Van Liew et al (1963) have pointed out and as Goodman (1964) has exploited, a large inherent unsaturation may be induced by oxygen breathing at normal pressures. Reverting to the original 1 atmosphere example, but substituting oxygen for air in the inspirate we may calculate as follows:

$$P_A O_2 \quad = \quad 673 \quad P_a O_2 \quad = \quad 638 \text{ (allowing for 35 mmHg A-a difference)}$$

$$P_A CO_2 \quad = \quad 40 \quad P_a CO_2 \quad = \quad 40$$

$$P_A H_2 O \quad = \quad 47 \quad P_a H_2 O \quad = \quad 47$$

Using the same oxygen extraction rate, the venous tensions may be calculated as:

$$P_V O_2 \quad = \quad 60$$

$$P_V CO_2 \quad = \quad 45$$

$$P_V H_2 O \quad = \quad 47$$

Total venous gas tension = 152 mmHg

This represents an inherent unsaturation of 608 mmHg, eleven times that present in breathing air.

By the same mechanism it may be calculated that the same driving force for gas elimination from bubbles exists at 6 atmospheres absolute breathing air and at 1.16 atmospheres (880 mmHg, $5\frac{1}{4}$ ft of water or 2.3 lb sq. in. (gauge)) breathing oxygen.

Herein lies the rationale behind the oxygen breathing regime of Goodman (1964). Using the writer's own method of calculation as shown above, the depths of 33 and 60 feet of sea water used in the tables of Figure 11-2 would yield inherent unsaturation of 1330 mmHg and 1400 mmHg respectively. The reason for the small difference between the two conditions is that at 60 feet (2.82 at. abs.) with the extraction rate assumed throughout these calculations, the venous blood would not only have fully saturated Hb but it would also have a $P_V O_2$ of about 650 mmHg because the oxygen in physical solution in the arterial blood is in excess of the tissue requirement.

Thus the limit of 60 feet, set from consideration of the limits imposed by the oxygen toxicity hazard, would also seem to be about the limit for usefulness on the basis of inherent unsaturation. This is hardly surprising because oxygen toxicity might be expected to occur when the tissue requirements are met by oxygen in solution and therefore the tissue oxygen tensions are many times their normal level.

The choice between the three regimes : full Table 4 compression to 6 atmospheres absolute, compression to the minimal pressure affording relief or minimal pressure + oxygen breathing, would seem to be open still. The extremely striking cases of recovery have been those of Donnell and Norton and of Bratt, both given the 6 atmosphere schedule. Cannon and Gould (1964) were in favour of early and adequate compression, but judged 3 atmospheres absolute as being optimal for the first stop on the basis that bubble size will be effectively reduced by a volume factor of 12:1 if the altitude of exposure was $\frac{1}{4}$ atmosphere, i.e. 34,000 feet. Goodman (1964) equally claimed good theoretical reasons and encouraging experimental outcome for the 3 atmospheres: 100% O_2 treatment. Kidd (1966) has found such a schedule extremely effective for diving or simulated diving cases.

The fear of conversion of an altitude case to a compressed air case is very real. There is certainly a risk that a person shown to be very susceptible at altitude will be equally liable to trouble during ascent from simulated depth. However, the latter form of decompression sickness is to be presumed to be amenable to treatment by re-descent. The rapidity of development of post-descent shock in altitude cases would suggest that any hesitation by way of wait-and-see procedures at depth is inherently dangerous. Half an hour waiting at 3 atmospheres in order to see whether symptoms are resolving is a highly significant period in a condition which has been known to cause death in under six hours.

The use of oxygen breathing to produce a very high bubble-to-tissue inert gas pressure gradient is very appealing theoretically but what do we know of the relationship between alveolar gas tensions and those in the neighbourhood of a bubble? Presumably the bubble has arisen because the local inert gas tension.was high relative to the ambient and therefore to the alveolar. Is it not likely that an area remote from a vessel with actively circulating blood is not only the ideal site for bubble formation but also the last place to have the tissue inert gas tension lowered by oxygen breathing? Again, time is of the essence and it would seem logical that whereas for removal of bubbles causing no more than local pain the oxygen therapy would appear reasonable, when the shock process is advancing the fastest possible method of bubble dissolution should be employed.

In order to diminish the size of bubbles there can be no speedier method than compression. It is the writer's opinion that the 6 atmosphere regime should always be adopted for cases where there is any suspicion of impending shock. Soaking at pressure is not to be recommended however, it can only lead to further accumulation of inert gas in both tissues and in pre-formed bubbles. Cautious decompression should be started as soon as conditions appear to be stable and Table 5A or 6A of the USN revised diving manual (Fig. 11-3) would appear reasonable. Recrudescence should always be taken as an indication for increased pressure. For cases without signs of shock, the USN 60 foot, intermittent O_2 Tables 5 and 6 are probably ideal (Fig. 11-4).

In the field of accidental gaseous embolism Vigouroux and Nivelleau (1960) would appear to be the first to have used high pressure therapy. They achieved a good result in a case of induced abortion with a combination of compression to 6 atmospheres absolute, hypothermia and intubation. Meijne, Schoemaker and Bulterijs (1963) claimed good results with oxygen at 3 atmospheres in the treatment of rabbits with induced cerebral air embolism, but their therapy was instituted immediately the blood pressure (systolic) fell to 50 mmHg or the EEG became silent. Rapin et al (1965) treated four cases of air embolism induced during abortion by compression to 2 atmospheres in oxygen. In one case the patient recovered, but there appeared to be no relationship to the treatment given and in the remaining three the therapy appeared ineffective. Admittedly the delay before treatment was six days, in one case, but the results in the other two were very disappointing. Fine (1963) advocated oxygen breathing for the treatment of air embolism, but Kylstra (1963) was strongly in favour of compression, citing, as has the writer, the importance of the immediacy of the effect on the bubbles.

Fati and Pallotta (1961) claimed that in the treatment of divers pressures in excess of 6 atmospheres were sometimes to be recommended, even when the diving depth had been such that the working pressure was considerably less than the 6 atmosphere equivalent, i.e. they recommended over-compression.

Oxygen breathing method for treatment of air embolism incurred during submarine escape training.

Table 5A

Depth (ft.)	Time (min.)	Breathing media	Total time (min.)
165	15*	Air	15
165-60	4	Air	19
60	20	O_2	39
60	5	Air	44
60	20	O_2	64
60 - 30	30	O_2	94
30	5	Air	99
30	20	O_2	119
30	5	Air	124
30 -0	30	O_2	154

*Total time will vary as function of this stop. Medical attendant should take enough time to accomplish a thorough physical examination, since the ensuing treatment is based on patient's physical status.

Table 6A

Depth (ft.)	Time (min.)	Breathing media	Total time (min.)
165	30	Air	30
165 - 60	4	Air	34
60	20	O_2	54
60	5	Air	59
60	20	O_2	79
60	5	Air	84
60	20	O_2	104
60	5	Air	109
60 - 30	30	O_2	139
30	15	Air	154
30	60	O_2	214
30	15	Air	229
30	60	O_2	289
30 - 0	30	O_2	319

Fig. 11-3. U.S. Navy tables, 5A and 6A. Reproduced from the amendment to the US Navy Diving Manual BUMEDINST 6420.2 of August, 1967.

Minimal recompression, oxygen breathing method for treatment of decompression sickness and air embolism.

Table 5

Depth	Time (min)	Breathing media	Total elapsed time (min)
60	20	O_2	20
60	5	Air	25
60	20	O_2	45
60-30	30	O_2	75
30	5	Air	80
30	20	O_2	100
30	5	Air	105
30-0	30	O_2	135

Table 6

Depth (ft)	Time (min)	Breathing media	Total elapsed time (min)
60	20	O_2	20
60	5	Air	25
60	20	O_2	45
60	5	Air	50
60	20	O_2	70
60	5	Air	75
60-30	30	O_2	105
30	15	Air	120
30	60	O_2	180
30	15	Air	195
30	60	O_2	255
30-0	30	O_2	285

Fig. 11-4   U. S. Navy tables, 5 and 6.   Reproduced from the amendment to the U. S Navy Diving Manual BUMEDINST 6420. 2 of August, 1967.

Other Therapeutic Possibilities

The literature contains accounts of animal experiments in which various agents
have protected against the effects of decompression. Mention has already been
made in this chapter of evidence for the value of heparin, heparin analogues, surface-
active agents and local anaesthetics.

Jullien, Leandri and Blein (1954) reported very briefly and almost without comment
on a protective action of adrenaline. Perhaps it acted as a bronchodilator, preven-
ting trapped gas barotrauma. This is a distinct possibility, since they used very
rapid decompression rates. Chryssanthou et al (1964) protected their obese mice
by "bradykinin antagonists" administered after decompression.

In man, Sicca and Lerza (1954) claimed that hypertonic sodium chloride solution
given intravenously relieved bends pain. No further work appears to have been
reported on this interesting but inexplicable observation.

Summary

No absolute rules may be layed down for the treatment of decompression sickness,
since cases vary enormously in their character and facilities for investigation and
treatment cannot be expected to be universally available.

Adequate diagnosis is the first essential and should include an estimation of the
packed cell volume or, a less valuable alternative, the haemoglobin concentration.

Symptomatic treatment is often the first available. Oxygen should be given in the
presence of cyanosis and paraldehyde is the best sedative drug should restlessness
be marked. Haemoconcentration should be treated promptly by intravenous infusion
of fluid, preferably dextran or plasma.

In any case showing deterioration, compression to high pressure should be instituted
at the earliest possible opportunity. To this end, compression chambers should
be provided at establishments where decompression is routinely carried out for
research, selection or training purposes. In the writer's opinion, initial treatment
of serious cases should be compression, air-breathing, to 6 atmospheres followed
by slow decompression as soon as is reasonable clinically. Only when symptoms
are very mild or facilities inadequate should lower pressures be used. If low
pressures of the order of 2 to 3 atmospheres are the greatest available, then inter-
mittent oxygen breathing should be used.

Since post-descent shock is very uncommon, few persons have seen more than one
case. There is much to be said for the organisation of a scheme for the immediate
availability of expert advice. For over fourteen years the writer has been called
upon for the majority of incidents and in many cases he has been able to give on the
spot advice within a few hours. In the United States where distances involved are
great, a team was established in 1962, to give a service on a 24-hour basis (Beyer,
1962). Six persons representing aviation medicine, internal medicine, surgery,
neurology, clinical pathology and laboratory technology were available at 3-hour
stand by and in three years their services were called upon seven times. On
one occasion only was it possible to give direct help by actual attendance at the
bed-side (Holmstrom and Beyer, 1965).

It is vital that at any airfield where high-altitude exposed aircrew are likely to land
and any site where decompression chambers are operated, medical officers should
be thoroughly trained in the principles of treatment and all should be aware of the
nearest recompression facility, the speediest mode of transport and the person to
contact to prepare the recompression chamber for use.

Where permanent establishment of a recompression chamber has not been considered necessary but other facilities are not available within an hour's travelling time. it would be extremely valuable to have centrally located within easy reach an air-portable single-man chamber in which the patient may be given treatment whilst in transit to a larger and more suitable fixed installation (Poggioli, 1966). Several such chambers have been produced, including a telescopic structure, a glass-fibre lightweight chamber and a flexible net-enclosed bag.

If neither a portable nor a fixed chamber is available, it is not unlikely that, with the current interest in hyperbaric oxygen therapy, a single-patient chamber capable of withstanding 2 or 3 atmospheres will be locally available. If so, the minimum pressure: 100% O_2 regime should be used.

The usefulness of the many other agents listed is debatable. Certainly the tendency to use any therapeutic agent as a substitute for compression is to be deprecated until it is clear that the results are comparable. To this end, experimental work is necessary. The relevance of small-animal high-pressure, rapid-decompression work is very doubtful. The best approach would appear to be the use of the high-pressure to subatmospheric method with dogs unless an altitude-sensitive animal preparation is found.

Note In compressed air parlance pressures are expressed as gauge, i. e. relative to atmospheric. Absolute = gauge + 14.7 lb/sq. in. Pressure is often referred to as equivalent water depth: 1 atmosphere = 33 feet of sea water.

12

Prevention

Introduction

The ultimate aim of medical studies should surely be prevention of disease.
Having considered so far the nature, origins, course and treatment of decom-
pression sickness, can we, from the knowledge gained, postulate valid means
for prevention? If prevention is either not possible or not practicable, can we
recommend measures whereby the serious hazards are avoided?

It is under these two headings, Prevention and Avoidance, that this chapter will
deal with these matters.

Prevention

If one assumes, from the evidence already cited, that bubbles of gas released
from solution are the basic cause of decompression sickness, then prevention of
bubble formation should be the fundamental approach to the prevention of decom-
pression sickness. The only means by which bubble evolution can be prevented
would seem to be the avoidance of supersaturation. To this end, several tech-
niques are available.

Maintenance of Equilibration

If ascent is so adjusted that gas emerges from solution only at the pulmonary al-
veolar membrane, all should be perfectly safe. The limiting factor here is
likely to be the rate at which gas can diffuse from the most remote depots to the
nearest blood vessel. Many attempts have been made to measure this, albeit
indirectly.

Boycott, Damant and Haldane (1908) calculated that the slowest desaturating tissue
took five and a half hours to lower its nitrogen content by 98%. Shaw et al (1935)
using anaesthetised dogs and following the wash out of nitrogen upon abrupt transfer
to pure oxygen, calculated whole body desaturation to be 95% complete at 112 to
184 minutes and complete at 154 to 240 minutes. Behnke (1945) claimed that in
man total desaturation occurred in 9-12 hours. Lundin, watching the nitrogen out-
put with an extremely sensitive nitrogen meter of his own design has obtained figures
for man of three compartments with half-times of 1.1-2.0 minutes, 12-13 minutes
and 100-200 minutes (Lundin, 1953 and 1960). Farhi et al (1962) following mixed
venous blood nitrogen content in anaesthetised dogs, have calculated that 5% of the
body nitrogen only is eliminated from a "fast compartment" which receives 50%
of the cardiac output. A further 7 to 15% of the nitrogen follows more slowly,
being served by 20 to 30% of the cardiac output, also 80 to 90% of the nitrogen is
served by only 10 to 15% of the cardiac output and has a time constant for elimina-
tion of 150 to 250 minutes.

It has often been suggested that some critical tissue exists and that it is the gas elimination rate from this possibly small site that is critical. Campbell and Hill (1933) studied goats and found 50% saturation times at 4 atmospheres of 3-5 hours for liver, brain and bone marrow, but the curves shown in their figures bear a rather optimistic relationship to the few points through which they are drawn. Jones (1951) made most extensive calculations from this and many other sources and also studied the movement of radioactive Xenon in the whole body. He deduced that there is, in man, a series of definable compartments, the slowest of which has a half time of the order of fifteen hours (Xenon compartment V).

How may this be applied? Pressure reduction at a certain very slow rate should be absolutely safe. We have already seen (page 78) that this was once calculated at 78 ft per min. but that an experiment at 50 ft per min. was not slow enough to prevent symptoms. The use of ft per min. rather than units of pressure per minute confuses the issue, but taking the rate at its highest (i.e. initially) gives a figure of 1.35 mmHg/min. On the linear basis of this decompression this would indicate that a decompression half time of 281 minutes significantly exceeds the rate of gas elimination, surprisingly in view of the experimental figures quoted above.

Whatever the safe rate might prove to be, it is clearly quite impractical in aviation. On the other hand, that such a rate exists is probable for those ascending to altitude by mountain climbing never appear to suffer from decompression sickness, although symptoms may be masked by the syndrome of mountain sickness of totally different origin.

Prevention of Bubble Formation by Limitation of Supersaturation Levels

That gas evolution in the form of bubbles is governed by certain degrees of supersaturation has long been recognised, although opinions expressed in the literature vary so widely, from Harvey's (1951) demonstration that in the absence of pre-formed nuclei no such phase-change takes place to Duffner's firm assertion that bubbles occur on every decompression (Duffner, 1962).

That gas should move from solution into a free gas phase as soon as any degree of supersaturation exists would at first thought seem improbable, although tap water allowed to stand in a glass rapidly develops bubbles on any possible source of micro-nuclei, presumably due to the inherent supersaturation arising from the rise from water-pipe temperature to room temperature.

Soviet authors have made particular studies of the Saturation Coefficients (SC) of various gases in solution, i.e. gas tension/ambient pressure at which bubbles first form. Aleksandrov and Brestkin (1964) found values of 2.03 to 2.43 for helium and 4.11 to 4.56 for nitrogen. The same authors found the Permissible Saturation Coefficient (PSC) at which symptoms first arise after six hours soak at raised pressure to be 2.40 for man breathing air and 2.66 for helium:oxygen mixtures. They expressed surprise at the reverse relationship between the SC and PSC values for the gases and concluded that factors of solubility and diffusibility also played an important part. Brestkin, Gramenitskii and Sidoro (1964) further extended the study to cover Safe Saturation Coefficients (SSC) at which symptoms never appeared and found that the SSC value varied with initial pressure. Studies on various gas mixture SSC's were also reported by Zal'tsman and Zinov'eva (1964). The SC values for air correspond well with the *in vitro* measurements of pressure changes needed to cause bubble formation in human serum, made by Downey et al in 1963.

The whole underlying assumption behind the regulation of decompression procedures for positive-pressure exposures is the performance of either staged or con-

tinuous slow pressure reduction. The fact that most procedures are based on a pressure drop to half absolute followed by further drops governed by a roughly 2:1 ratio fits well with the SSC concept, but the selection of ratios rests on experimental evidence not on any theoretical derivation. Tremendous advances have been made in decompression table computation by the use of electronic and pneumatic analogue computers (Stubbs and Kidd, 1965A and 1965B), but again the programming is based on human experimental data after complex calculations have been indulged in to justify the use of such data.

Hills (1966) has recently challenged the whole concept behind most of the world's decompression schedules yet again because of the emergence of data from human experimentation, in the form of certain diving schedules adopted by divers operating in the Torres Straits (Le Messurier and Hills, 1965). These recent figures can be supported by a thermodynamic approach to calculation and the recognition of inherent unsaturation.

Nevertheless, tables or computer read-outs are used in diving and compressed air work on the basis that they have been proved to result in an acceptable decompression sickness incidence of around one per cent of all man/exposures. In aviation it is impossible to programme ascents to conform to such calculations. Indeed, although Stubbs and Kidd's computer has an altitude extension of the depth scale starting at sea level, it merely indicates that ascent is unsafe above 18,000 feet.

The conclusion must be that prevention or limitation of super-saturation by adjustment of ascent rates is not a feasible proposition.

Prevention of Bubble Formation by Limiting Pressure Reduction

A simple approach to the prevention of decompression sickness is to limit the altitude and the time of exposure to a proven safe level. This is not practicable in most circumstances if it involves keeping the flight altitude and duration to levels known to be safe; for example, aircraft cannot be restricted to ten minute flights above 18,000 feet. However, the immediate environment of the aircraft occupant may be so controlled in terms of pressure, by the use of a pressurised or sealed cabin or a pressurised suit.

Pressure Suits - These have the longer history. The first suggestion for their use was made by Haldane in 1922, although he conceived of the suit as a means of preventing hypoxia above 40,000 feet, at which altitude pure oxygen at ambient pressure exerts insufficient pressure to maintain an adequate arterial oxygen tension. The fascinating history of the implementation of this concept in the USA by Wiley Post (McMurry, 1963; Wilson, 1965), in the UK by Swain and Adams, using a suit designed by Haldane and Sir Robert Davis (Anon, 1936), in France (Rosenstiel, 1935) and in Russia (Wilson, 1965) is beyond the scope of this work. The reader is referred to an excellent review by Wilson (1962).

Suits currently in use are of two types, full and partial. The former encloses the whole body in a form-fitting gas-tight envelope, the latter exerts counterpressure by fabric or inflatable bladder contact over part of the body only. In either case the mechanical problems of strength and mobility have meant that internal pressures are limited to about 3.5 lb/sq. in. (181 mmHg). In order to prevent decompression sickness completely an internal altitude of 18,000 feet would seem essential (see Chapter 5). This would mean that the aircraft ceiling would be limited to 33,000 feet with the suit in operation. Such a limit is intolerable in operational conditions and the suit is therefore limited to a primary role of hypoxia prevention and a secondary role of decompression sickness incidence reduction. Partial pressure suits are much less effective in the latter respect than

are full suits, because the unpressurised areas are mainly those in which symptoms are likely to arise, i.e. the joints and extremities.

The only pressure suits likely to prevent decompression sickness entirely are those so-called "hard suits", comprising of articulated rigid components or specifically designed high-pressure flexible suits which in the current state of the art must present considerable restraints on mobility. The only example of the latter class of suit would appear to be that used by the Soviet cosmonaut Leonov in 1965. This space-suit has been reported as being pressurised to 0.4 atmosphere (304 mmHg) corresponding, in space conditions, to 23,500 feet.

Pressurised Cabins - These have a history dating back to the 1920's (Brown, 1966). The pressure level selected has been a matter of compromise between strength (and thus weight), risk of rupture and physiologically desirable sea-level pressure. Many military aircraft have been designed with pressure cabins which maintain 25,000 feet internal altitudes at the maximum operating altitude of the aircraft in deference to the weight and hazard questions. This level was selected largely on the basis of knowledge available in 1941-1942 and it has been found quite clearly not to prevent decompression sickness. In order so to do, an internal altitude of 18,000 feet or slightly below would be necessary. Transport aircraft have a high differential cabin, maintaining about 8,000 feet internally and are therefore quite safe. A few current generation military aircraft are being provided with intermediate pressure cabins which will provide a safe or nearly safe milieu.

Elimination of Inert Gas (Denitrogenation)

In Chapter 5 we have already considered the effects of altitude of residence and have seen that decompression sickness would be prevented by maintaining personnel at reduced pressure for some time prior to altitude exposure, although we have insufficient experimental evidence to be able to specify exact levels and times for any given final height of exposure. The actual application of this idea would appear quite impracticable, although it has been serious'y considered that spaceflight personnel should be maintained in a low-pressure crew room for several days before launch, in order to reduce the hazards of subsequent altitude exposure in the space vehicle or in extra-vehicular suited excursions. The problems of transfer would seem to be formidable.

The more practical way whereby inert gas may be eliminated is by replacement of part or all of the inspired nitrogen in the air by oxygen, so called pre-oxygenation. The origins of this manoeuvre are not known but the principle was already known in 1906 (von Schrötter). A vast amount of effort was put into the investigation of pre-oxygenation in the USA during World War II and extensive reviews were prepared in 1951 by Bateman and by Jones. The variable results obtained are characterised by the highly complex diagram from Jones's paper shown in Figure 12-1.

There is no doubt whatsoever that pre-oxygenation protects against decompression sickness and that the degree of protection is related to the degree of denitrogenation. The actual mechanism whereby elimination of nitrogen protects is rarely discussed, however. The general assumption is made, unquestioningly, that inert gas is the aetiological agent in decompression sickness and that replacement of the inert gas the act've gas O_2 will eliminate the hazard. But how? Surely if a person saturated at 1 atmosphere pressure with any gas mixture compatible with life will be in a state of supersaturation at altitude and will thus be liable to bubble formation. To the question "why not decompression sickness due to oxygen bubbles?" the usual reply is that they are metabolized.

The solubility of oxygen in body fluid is quite high, 0.3 ml O_2/100 ml fluid/100 mmHg tension and although it is not possible to estimate a mean whole body oxygen
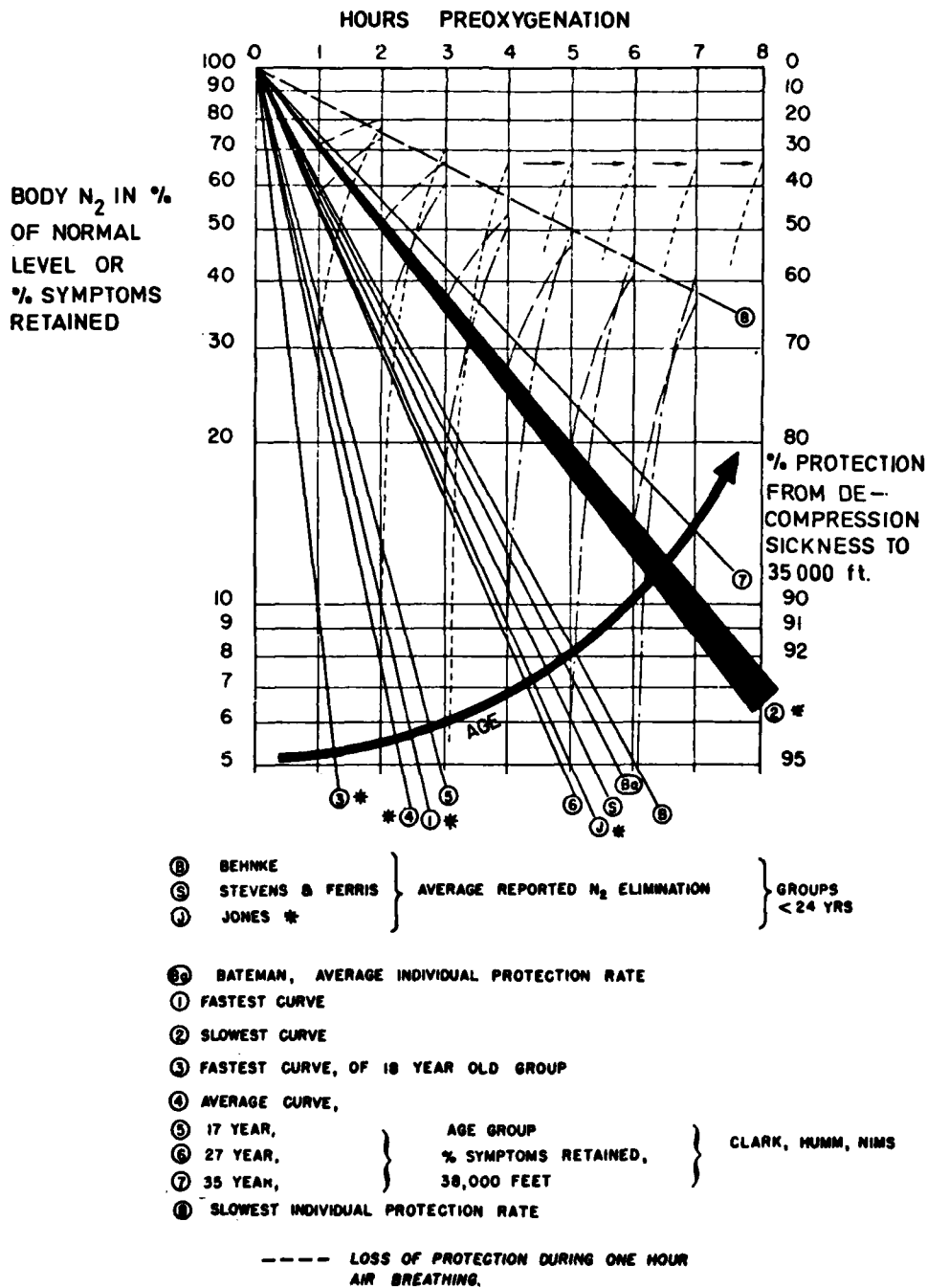
Fig. 12-1 A survey of the protective value of pre-oxygenation.
Figure from Jones (1951).

tension, the body must contain a very considerable quantity of oxygen in physical solution after pre-breathing oxygen at sea level for several hours. Rapid ascent, say in a matter of a very few minutes, should lead to bubble formation. Indeed, Donald (1955) has claimed to demonstrate the occurrence of oxygen bends in goats decompressed from raised pressure. Metabolism could account for rapid removal of oxygen once liberated, 240 ml O_2 (STPD) per minute being a representative figure for a young adult male at rest, but the distressing effect of intravenous administration of oxygen at 6 to 10 ml/minute (see page 60) would indicate that bubbles of this gas in the pulmonary circuit are not very rapidly removed. Admittedly in the condition of intravenous administration nitrogen would diffuse into the bubbles from the venous blood whereas in the pre-oxygenated man this would not occur.

There is a much simpler explanation which has hitherto not apparently been proposed, other than in a passing reference in Hills (1966). The key lies in the theory of inherent unsaturation already discussed in Chapter 11. In oxygen breathing at sea level an imbalance of some 600 mmHg exists between the total tension of gases present at the venous end of the capillary network and ambient pressure. Reduction of atmospheric pressure by such an amount, equivalent to ascent to approximately 37,000 feet, should thus be without danger of bubble formation. This compares most favourably with the inherent unsaturation level of 55 mmHg air breathing at sea level, equivalent to only 2,000 feet!

Obviously at the arterial and intermediate levels of the capillary and its surrounding tissue such a buffer is considerably less extensive, but nevertheless the arterial blood will be in equilibrium with the alveolar gas in the lungs, at the time at which it passed through the pulmonary capillaries and can only be super-saturated to the extent that the ambient pressure has fallen between the passage through the lung and arrival at the tissue.

Thus it would appear that the rather unsatisfactory explanation for the harmlessness of evolved oxygen bubbles in pre-oxygenated man is rather academic, since it can be postulated that inherent unsaturation is such as largely to preclude bubble formation on ascent.

Practical considerations make pre-oxygenation of relatively little operational value. To pre-oxygenate adequately for a typical military flight in an unpressurised high altitude aircraft would entail the aircrew member having to wear a tightly-fitted oxygen mask for over an hour before flight, during briefing and during transportation to the aircraft, with no breaks in the continuity of the denitrogenation. To do so would be irksome, would impede mobility, would raise difficulties in communication on the ground and, in the case of early morning flights, would prolong duty hours to a significant extent.

Pre-oxygenation is currently almost entirely restricted to a few specific circumstances. These are research and training in decompression chambers, high altitude flight with a high probability of cabin pressure loss, space flight and for protection of known highly susceptible individuals.

Research and Training - In decompression chambers it is generally most undesirable that altitude exposure should be complicated by the occurrence of decompression sickness. As a general rule, if the total time of an altitude above 18,000 feet is likely to be in excess of ten minutes it is recommended that pre-oxygenation is carried out. Experienced personnel with a well-established assessment of susceptibility may, for convenience, ignore this principle if they judge the risk to be slight in comparison with the inconvenience, but this should not be done lightly. For the training of aircrew in the use of oxygen equipment it is most important that

the hazards of the procedure should be minimised and in a well equipped and organised training establishment it is possible to arrange facilities so that lectures or study may be carried on during the pre-oxygenation period.

The optimum length of the pre-breathing period is difficult to specify because one is chary to reduce the period experimentally until a case occurs, for by so doing one may lose the confidence of the trainees.

In the USAF it is standard practice to pre-oxygenate for twenty minutes before an altitude indoctrination procedure involving ascent to 43,000 feet followed by hypoxia demonstration at 25,000 feet. Under such circumstances, in a series of 20,000 exposures, eleven cases of illness requiring admission to hospital were reported by Cutler in 1962. Of these five were undoubtedly associated with decompression sickness, four experiencing bends and one bends and chokes.

In the RAF, before training procedures involving rapid decompression and brief exposure of up to one minute at altitudes between 48,000 and 70,000 feet and descent over some five to ten minutes, depending upon the equipment in use, it has been routine procedure to pre-oxygenate for one hour. The writer has analysed the records for 7685 such runs and finds the results to be as follows:

Table 12-1   Data from high altitude training decompressions in the RAF

Total exposures	Unspecified pain*	Bends	Formication
7685	2	1	1

* Almost certainly pains in arms during pressure breathing without arm counterpressure; not in any way related to decompression sickness.

The results would appear to be very satisfactory and probably significantly better in terms of definite decompression sickness than the equivalent USAF figures, quoted above.

High Altitude Flight with High Probability of Cabin Pressure Loss - This is rare but is disquieting because it is often undertaken in conditions such as to make descent to low altitude impracticable, since aircraft range is considerably reduced in the case of turbo-jet powered aircraft flying low.

Meader (1963) has analysed the incidence of symptoms in a series of over 1000 flights by WU-2 very high altitude weather reconnaissance aircraft of the USAF. In this type a cabin altitude of 29,000 feet is usual and decompression has occasionally occurred at altitudes of 45,000 feet to over 60,000 feet, presumably in association with engine-stalling problems at these heights. Flights are generally of three to seven hours duration. Pre-oxygenation is routinely carried out for thirty to sixty minutes and it is obviously reasonably effective since Meader's figures revealed thirty-six cases of bends pain and no other symptoms. Of the thirty-six episodes, nineteen affected one pilot and exclusion of this highly susceptible individual gives a bends rate of 0.17%, a very commendable figure.

No equivalent data are available for RAF operational flying.

Another source of high altitude flight risk is test flying, for in early stages of development deliberate unpressurised flights are often performed. A typical example is the requirement for military types to be test flown without the canopy in

order to assess the degree of aerodynamic suck which may be quite significant
when it is necessary to decide upon the safe operational ceiling of that type for
aircrew using specific types of oxygen equipment.   In such flights pre-oxygenation
is highly desirable.

Space Flight - There are two stages in which decompression sickness represents a
hazard.   Cabin pressure cannot be maintained in flight by compressors for there
is no external atmosphere.   Sealed cabins are constructed, but because of the con-
straints imposed by the very high launch vehicle: payload weight ratio, the US
National Aeronautical and Space Administration (NASA) has found it necessary to
adopt a maximum cabin pressure of 5 to 5.5 lb/sq. in., equivalent to 25,000 to
27,000 feet.   This pressure level brings a definite hazard of decompression sick-
ness, even for short duration flights.

Also, there is an additional hazard, that of loss of spacecraft cabin pressure.
This may result from leakage or may be intentional either to allow extra-vehicular
activity or to extinguish a fire.   In either case, the space traveller depends upon
his pressure suit and in the US case, this has an internal pressure limit equiva-
lent to some 35,000 feet.

To combat the risks of the occurrence of symptoms during both routine flight and
in the event of reliance on their pressure suits, all US astronauts have pre-
oxygenated at ground level for several hours by the simple measure of purging
the craft with oxygen before launch.   The prolonged pre-oxygenation and the
maintenance of a 100% oxygen cabin atmosphere throughout the flight has sufficed
to protect all the participants in the Mercury and Gemini flights, including several
depressurisations in the latter series.

In the Soviet spacecraft of the Vostok and Voskhod series, the cabin atmosphere
was of air or near-air composition at 1 atmosphere pressure.   This brought a
bonus in the form of complete exclusion of the decompression sickness risk in
routine flight but a considerable problem if depressurisation were to be under-
taken.   On the only known occasion, when Leonov carried out his extra-vehicular
sortie from Voskhod 2, the hazard was reduced by both the high suit pressure
already referred to and, it is believed, a one hour period of pre-oxygenation
(Gatland, 1967).

Protection of Known Highly Susceptible Individuals - This is occasionally necessary,
although every effort should be made to exclude them from exposure.   Sometimes
in research it is found that an individual has become increasingly susceptible whilst
his skills and experience have simultaneously increased.   It may be necessary for
him to carry out research in decompression chambers or in flight because he alone
can carry out the job in hand fully effectively.   A particular example is that of a
Chief Test Pilot who was known to be highly prone to develop symptoms of a severe
nature when exposed to high altitudes, but nevertheless was categorically stated to
be the only person capable of carrying out to full advantage certain flights in a pro-
totype aircraft which was, at that stage, unpressurised for structural reasons.
In his case it was necessary to insist on the provision of facilities for pre-oxygen-
ation and to ensure their use.
Pre-oxygenation at Altitude - This is a very attractive proposition.   In any open-
circuit (i.e. non re-breathing) oxygen system, a very large proportion of the oxy-
gen is wasted and in an aircraft the quantity of oxygen carried may be insufficient
for pre-flight pre-oxygenation.   If, however, one could depend upon there being a
period of flight in which the decompression hazard was minimal, a considerable
saving in oxygen could be achieved by selection of a cabin altitude well above sea
level.   For example, oxygen consumption could be halved by pre-oxygenation at
18,000 feet.   An even greater saving would be possible at 25,000 feet.   In order
to examine this question the writer carried out series of experiments in 1953, in
which many lessons were learned.
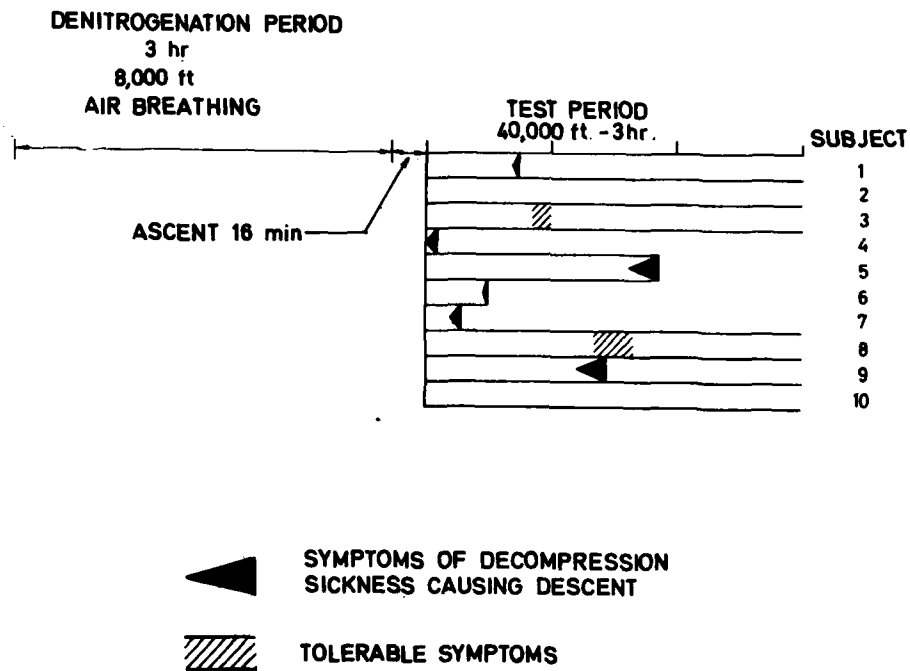
Fig. 12-2 Results of denitrogenation by air-breathing at 8,000 feet prior to ascent to 40,000 feet.
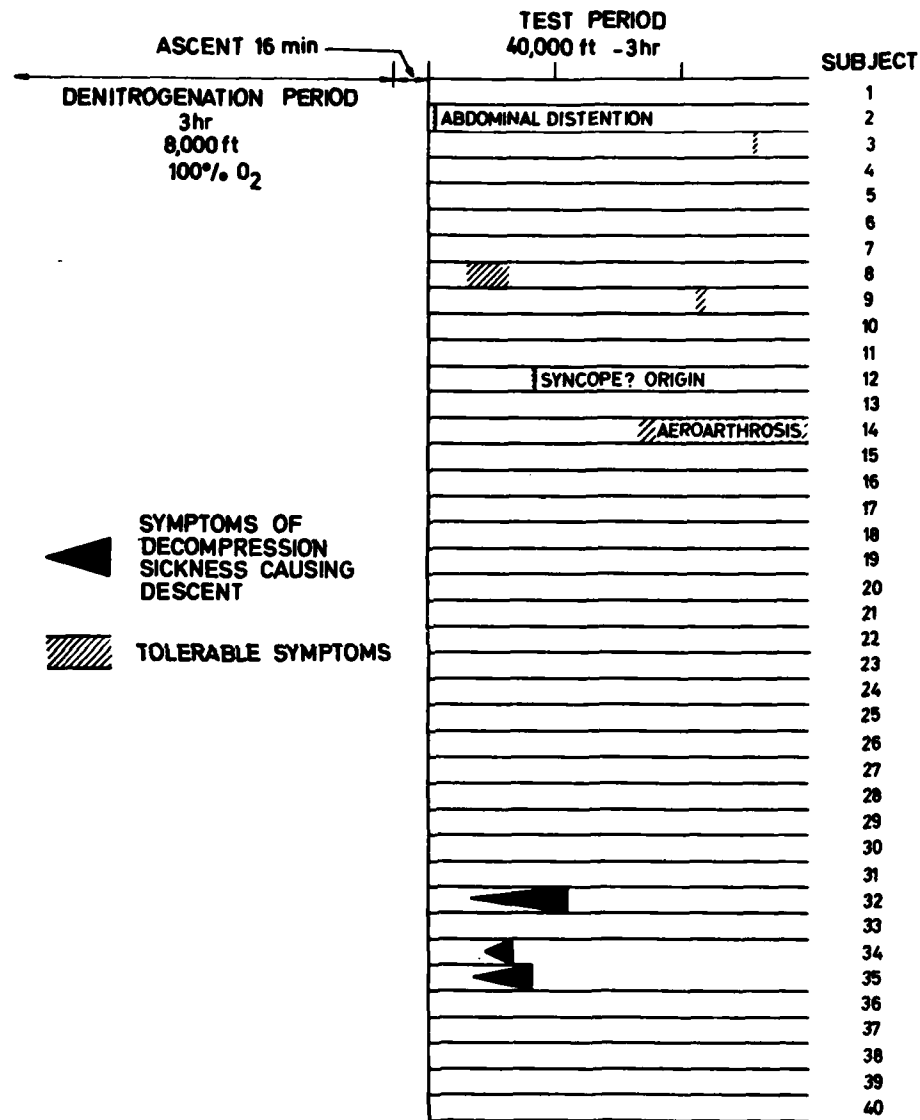
Fig. 12-3 Results of denitrogenation by oxygen-breathing at 8,000 feet prior to ascent to 40,000 feet.

ASCENT 16 min

TEST PERIOD
40,000 ft -3hr

SUBJECT

DENITROGENATION PERIOD
1½ hr
8,000 ft
100% O₂

ABDOMINAL DISTENTION

AEROARTHROSIS

SYMPTOMS OF
DECOMPRESSION
SICKNESS CAUSING
DESCENT

TOLERABLE SYMPTOMS
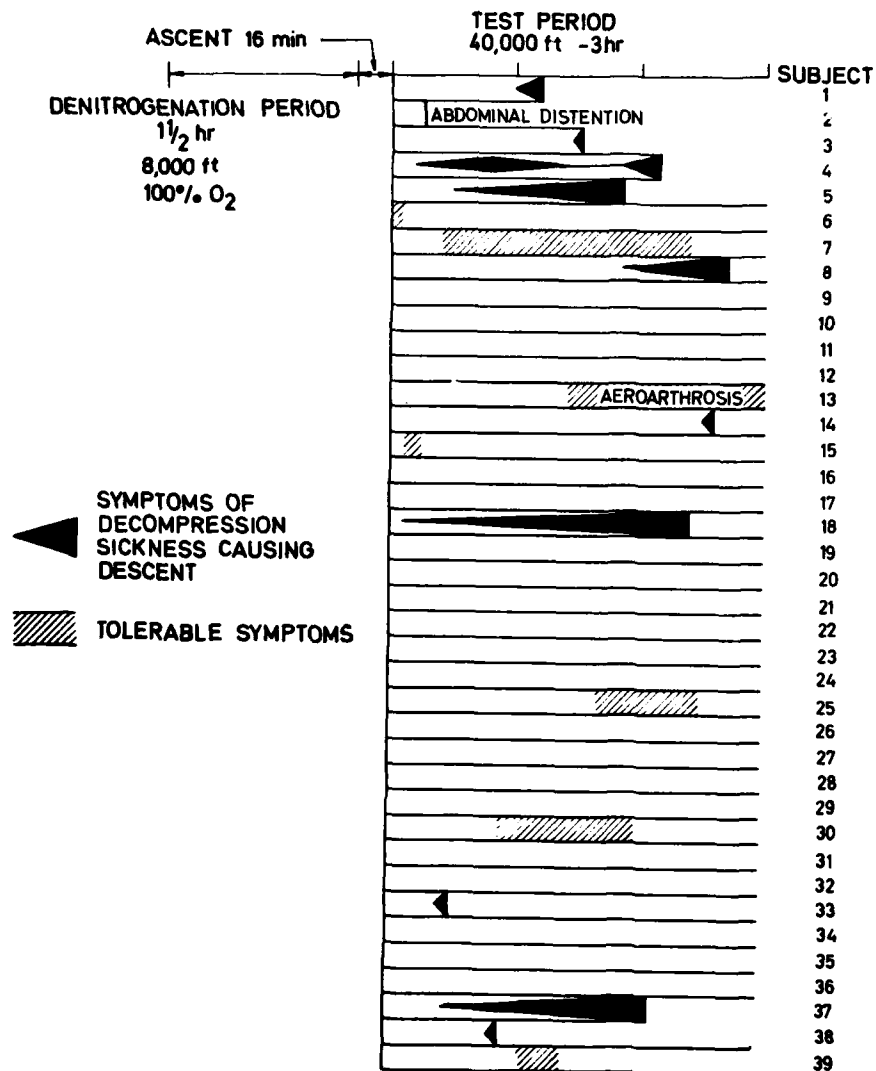
Fig. 12-4   Results of denitrogenation by oxygen-breathing at 8,000
feet for a shorter period than in Figure 12-3, prior to
ascent to 40,000 feet.
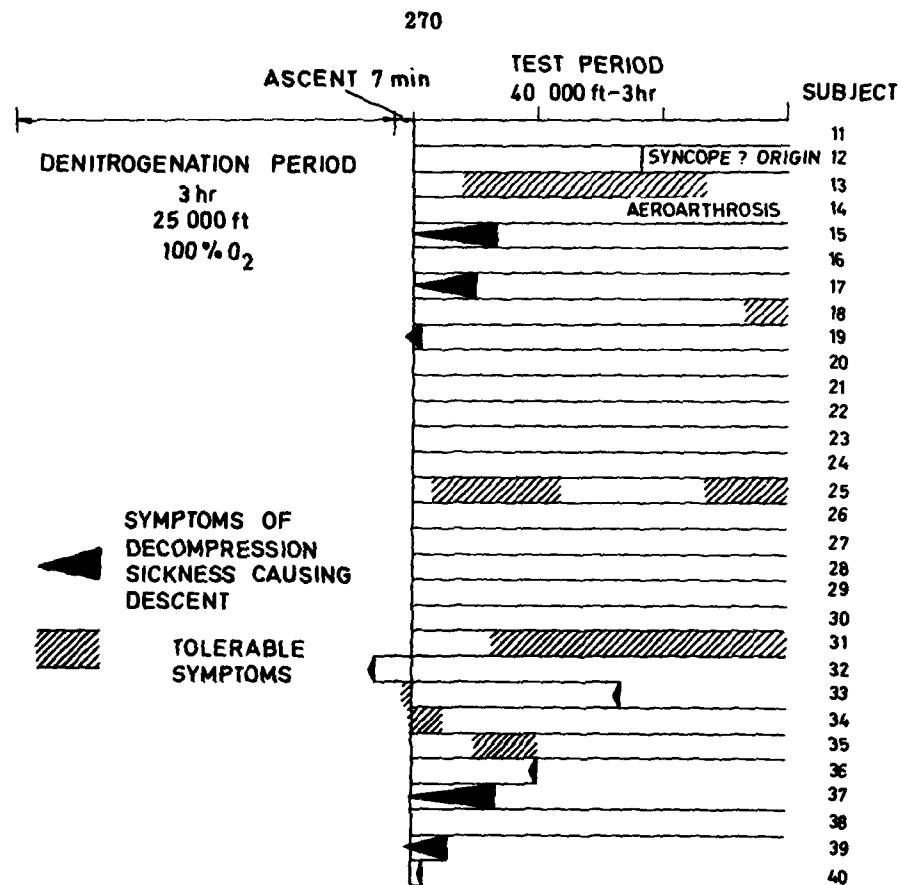
Fig. 12-5 Results of denitrogenation by oxygen-breathing at 25,000 feet prior to ascent to 40,000 feet.
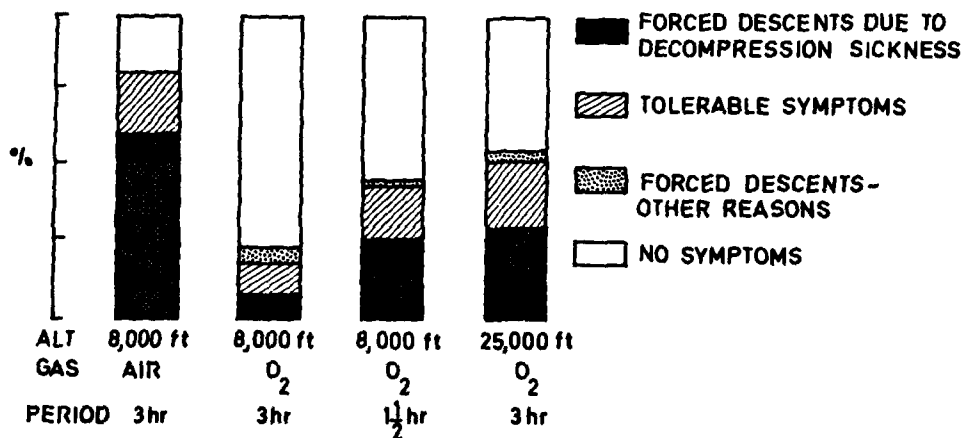
Fig. 12-6 Comparison of the effectiveness of the four forms of denitrogenation procedure illustrated in Figures 12-2 to 12-5 inclusive.

The simulation was made as realistic as possible, in order to achieve a reasonable assessment of the usefulness of pre-oxygenation in a foreseeable operational situation. The study was based on the V-bomber aircraft then being developed for service and which had an optional cabin pressure setting of 8,000 feet (cruise) or 25,000 feet (combat). The possibilities therefore existed of denitrogenation by air breathing at 8,000 feet, by oxygen-breathing at 8,000 feet or by oxygen-breathing at 25,000 feet. A flight profile of up to three hours outbound, pressurised, followed by three hours return at 40,000 feet after cabin pressure loss was chosen as realistic and groups of ten volunteers from among the aircrew of Bomber Command were used as subjects. The sequence of runs was randomised, each subject having three exposures on alternate days, but conditions which were obviously unacceptably severe were abandoned and different profiles substituted for the next group.

Four groups of ten subjects were tested, a total of 120 man/runs in all. The results are summarised briefly in Figures 12-2, 12-3, 12-4 and 12-5.

The control situation of air breathing at 8,000 feet for three hours, followed by ascent was obviously unacceptable and was used once only (Fig. 12-2). Even then it was abandoned before the three hours were completed as there were 6/10 forced descents, 2/10 minor symptoms (itching and bends) and only 2/10 symptomless.

Three hours pre-oxygenation at 8,000 feet proved very successful in reducing the incidence of symptoms (Fig. 12-3). There were only 3/40 forced descents, all for bends, 4/40 men with tolerable symptoms of mild discomfort in skin or joints and 31/40 symptom-free. Two remaining subjects had to descend for reasons other than decompression sickness; one developed a febrile illness and the other had intolerable abdominal distension as soon as the climb was completed.

Reduction of pre-oxygenation time at 8,000 feet to one and a half hours brought about a much less satisfactory result (Fig. 12-4). Of thirty-nine subjects (one was withdrawn from the trials after having very severe chokes) there were 10/39 forced descents for decompression sickness, 7/39 tolerable symptoms and 21/39 symptom-free subjects. One (the same man as in the previous series) descended for abdominal distension of extreme severity.

The 25,000 foot pre-oxygenation was relatively ineffective (Fig. 12-5). Of thirty men exposed 9/30 were forced to descend, 7/30 had tolerable symptoms and only 13/30 were symptom-free. One remaining subject had to be withdrawn for what might have been an intercurrent illness or a psychological reaction.

The overall outcome of these trials (Fig. 12-6) was to show that air breathing at 8,000 feet for three hours was useless as a prophylactic measure before ascent to 40,000 feet. On the other hand, three hours pre-oxygenation at the same height was almost completely effective. Reduction of the oxygen-breathing to one and a half hours greatly reduced the effectiveness although most subjects were protected for the first hour of exposure.

By comparison with the previous conditions, pre-oxygenation at 25,000 feet was very unsatisfactory. Symptoms during the ascent or within five minutes of reaching 40,000 feet were reported by four of the thirty subjects, no doubt indicating the presence of silent bubbles.

It would be of considerable practical value to know the maximum altitude at which pre-oxygenation could be carried out without incurring silent bubble formation. American experiments aimed at the assessment of possible space-craft atmospheres have shown that 17,000 feet is too high, but the band between this and

and 8,000 feet would appear to be almost totally unexplored. Marotta et al (1961) were concerned with air-breathing at altitudes up to twelve hours at 12,000 feet, but did not use oxygen.

Hazards of Pre-oxygenation - These are few but cannot be dismissed. Removal of inert gas from the alveoli brings about a most important alteration in pulmonary physiology. Cessation of ventilation, whether induced by impacted secretions in bronchi, poor diaphragmatic excursion or mechanical splinting leads to rapid absorption of alveolar gas until atelectasis supervenes (Glaister, 1965; Ernsting, 1965). The result is the creation of a physiological arteriovenous shunt in the lungs. Although the degree of such collapse is slight at rest, acceleration in any axis can produce massive collapse and it is established British policy that 100% oxygen breathing should not be normal practice in aircraft in which violent maneouvres are carried out. Re-expansion is normally rapid upon deep breathing or coughing, but in some subjects there is detectable mal-ventilation for many hours after reversion to air-breathing. No long-term effects are known, but Gable and Townsend (1962) reporting on histological examination of lungs from victims of aircraft accidents, claimed that aircrew showed a high incidence of pigmented alveolar macrophages and that five of sixty specimens examined showed alveolar septal thickening. Unfortunately their control series of ten road accident victims was much too small to allow any assessment of the significance of the latter finding.

Oxygen poisoning is an unlikely sequel to pre-oxygenation as normally practised, but altered pulmonary function has been detected after no more than three hours of oxygen breathing at sea level (Ernsting, 1961).

Finally, a risk which has most recently been acknowledged is that of increased ignitability and inflammability of material in an oxygen environment. Prolonged wearing of oxygen masks or closed pressure helmets is irksome and for this, among other reasons, the US policy in the Mercury and Gemini space vehicles was to carry out pre-oxygenation by filling the craft with oxygen and allowing the astronauts to have their visors open. However, the disastrous fire in an Apollo capsule in 1967, in which three men died, has le ' to a decision to revert to a closed-visor, air-filled cabin policy.

Avoidance

If, as has been seen, practical considerations preclude total prevention of decompression sickness, much may be done to reduce the incidence and severity of cases. The relevant measures can be considered under three headings; reduction of exposure, detection of susceptible persons and prompt handling of cases.

Reduction of Hazardous Exposure

Although a total ban on flight at cabin altitudes above 18,000 feet is unacceptable, it is possible to apply certain limits on flying profiles without reduction of operational efficiency. For example, unpressurised aircraft such as the Jet Provost trainer are subject to limits of no more than ten minutes flight at 35,000 feet and thirty minutes above 30,000 feet per sortie and crews are subject to limitations on the numbers of sorties per day. In those aircraft with optional pressure cabin settings of 8,000 feet and 25,000 feet, the latter setting is now used only for certain exercises and then for limited periods.

In the event of loss of cabin pressurisation, descent to the lowest possible altitude should be carried out as soon as possible and with this in mind long endurance flights should, whenever possible, be carried out over routes which will allow return flight at low altitude to the nearest base should such an emergency occur.

In addition to altitude and duration limitations, those factors which increase the probability of the occurrence of symptoms should be reduced as far as possible. Thus aircrew and passengers in aircraft with high cabin altitudes should be kept as warm as possible and they should avoid strenuous physical exercise. Adequate oxygenation is essential.

Detection of Susceptible Persons

If the exposure of personnel to hazardous altitude cannot be totally excluded, the incidence of symptoms may be reduced by the exclusion, so far as is possible, of the more susceptible personnel. This may be achieved by two approaches, the restriction of flying by those groups known to have a high incidence compared with the average or by actual selection by simulation.

The groups of high susceptibility are primarily the older and the obese. However, exclusion of these categories arbitrarily would lead to unnecessary restriction in that both groups undoubtedly contain many low-susceptibility individuals. Temporarily enhanced susceptibility is a more reasonable assumption and to exclude flying by those with recent skeleto-muscular injury, those with hang-overs and personnel who have recently been exposed to compressed air, is a very wise and not unreasonable precaution.

Henry and Ivy (1951) have reviewed the assessment of nitrogen eliminating ability by radioactive gas studies and Lundin (1960) related bends susceptibility to nitrogen elimination rates, but neither technique would appear to offer a high enough reliability to be acceptable as a selection method.

The direct selection method, by actual simulation of altitude would appear to be the most realistic means available and to this end several hundreds of thousands of decompression chamber tests have been carried out in the United States of America and in Great Britain.

In RAF practice it has generally been accepted that a potentially dangerous flight regime is sufficient indication for a selection test. Thus, if a man is going to react adversely he is likely to do so in a decompression chamber under medical observation rather than in the much less favourable conditions of actual flight. During the 1939-1945 war two particular tests were employed. For the crews of the RAF's few B-17 Flying Fortress aircraft obtained from the USA a very severe test of four hours at 35,000 feet was chosen (Russell, 1943). For the aircrew operating photographic reconnaissance aircraft which flew at maximum altitude for long periods, three exposures of two hours at 37,000 feet on alternate days were used (Morant, 1952; Cotes and Gronow, 1952). Simple fail or pass categorisation was based on the severity of the symptoms.

In the USA there were many procedures evolved, but under the guidance of a subcommittee of the National Research Council in 1943, a Standard ninety minute test was evolved (Henry and Ivy, 1951). This test included exercise periods, a common feature of American tests. Results were based upon a reaction score points system. Very extensive surveys of this test, its development and its validation have been reviewed by Henry and Ivy, who were so deeply involved in its inception.

In the post-war period testing has been intermittently applied. For several years it was standard RAF practice to test those aircrew involved in research flying by a single exposure at 37,000 feet for one hour. The Royal Navy for many years used a similar height and duration but exposed all aircrew to three such runs on alternate days. The results were assessed on a three class system; category A being those without symptoms, category B those who experienced mild or moderate symptoms with reasonably slow onset and category C those with very severe

symptoms. Category A were unrestricted, category B were restricted to specific low altitude flying duties, but together with category A personnel were re-tested every four years. Category C personnel were both restricted and also excluded from further testing (Gould, 1963).

With the introduction of the Canberra bomber into service in the early 1950's, the RAF applied a test based on a new principle. This was the first British long endurance military jet aircraft and the fear was that the personnel might not prove capable of bringing an aircraft back to base after loss of cabin pressure over target. Therefore a test was introduced in which aircrew were subjected to an hour at 25,000 feet followed by a rapid ascent to 37,000 feet for a further hour. The results of the test were assessed on a pass or fail basis. After several years experience it became clear that the hazard of actual cabin pressure loss was extremely small and the test was subsequently abandoned.

In 1954 a new test was introduced, reverting to the concept of assessment of ability to tolerate normal, as opposed to emergency, conditions. It was felt that it was both dangerous to employ aircrew unable to tolerate conditions likely to be encountered in routine flight and wasteful to train new crews who were similarly susceptible. The worst case operating condition was chosen as 28,000 feet cabin altitude, a level likely to be encountered both in old and therefore leaky aircraft, originally built to a 25,000 foot cabin specification and, much more important, in developed versions of such aircraft whose operating ceiling had been raised by aerodynamic and powerplant changes. A period of two hours was also chosen as a reasonably representative endurance and since the incidence of symptoms was expected to be very low, a duplicate run after an interval of two to thirty days was included. Clearly defined pass and fail criteria were specified. The results have been dealt with in Chapter 6.

When the Canberra role changed and prolonged 25,000 foot cabin flight became less common in the early 1960s, this test was discontinued, but one class of pilots remained at high risk. These are the instructors flying the unpressurised Jet Provost aircraft. They are regarded as significantly at risk in view of both their age and exposure frequency compared with their pupils. As a result a reasonably realistic test profile has been developed comprising of 50 minutes at 20,000 feet, 20 minutes at 30,000 feet, a further 40 minutes at 25,000 feet, reascent to 30,000 feet for 20 minutes and finally 10 minutes at 20,000 feet, the whole run including climb and descent totalling three hours.

The justification of tests has very often been questioned. Certainly the war-time tests led to a reduction of reported incidents in flight (Russell, 1943), but against this must be weighed one RAF fatality, nine US and one Canadian, all during tests or training procedures in decompression chambers (see Chapter 8). The writer has been most impressed by the low proportion of in-flight cases who have previously been tested and the high-risk individual in the RAF for many years was the man who somehow slipped into high altitude duties without screening by decompression testing. The relevance of chamber tests to in-flight experience is often queried by aircrew, but the work of the University of California group who compared test results with the actual outcome of prolonged flights in B.17 and B.24 aircraft would seem to offer full validation (Tobias, 1951).

Tests should fulfil several basic criteria. They should be justified, well supervised, uniform and fairly assessed. To deal with these criteria in turn:

The Justification - This should be that the test should be representative of the condition for which selection is to be applied, both in terms of height and time.

Supervision - This should ensure that tests are conducted with the minimum of risk to those tested. In particular a very high standard of training of staff is essential.

Uniformity - This must be insisted upon, in that scrupulous fairness is essential. Exercise at altitude is difficult to arrange and can rarely be applied in such a way that one can be certain that an identical level of exertion is imposed on all. Rest is at least well-defined and understood by lay persons. Clearly laid-down test procedures, including ascent rates, oxygen regulator settings and between-test intervals should be adhered to.

Fairness of Assessment - This is the key to success, both in practical terms and also in acquiring the confidence of aircrew. To this end it is mandatory that symptom levels should be as adequately defined as possible, assessors trained carefully, criteria established for fail or pass and reporting channels specified. It has been RAF practice for many years that where any doubt exists about the result of a test, the person concerned should be seen and reviewed by both the Command Flying Personnel Medical Officer and by an Aviation Physiologist or Medical Specialist at Farnborough, in order that any doubt about the diagnosis and any underlying factors should be reduced to a minimum. Finally, wherever possible duplicate tests should be employed, in that these give a clearer indication of susceptibility, particularly to the subject, than does a single exposure. Morant (1962) has assessed the usefulness of multiple tests and it would appear that two tests are much more valuable than one, but that a third offers little extra.

Prompt Handling - As a final attempt to reduce the toll of decompression sickness it is essential that cases, when they occur, should be so handled as to minimise the risk to the individual. Education is essential. Aircrew should be taught how to recognise decompression sickness, where and when to anticipate risk and how to handle any incident. Medical staff should be thoroughly grounded in the diagnosis and treatment of decompression sickness and post-descent shock.

It is not easy to run the narrow course between failure to teach aircrew sufficient about the hazards on one hand and the raising of unjustifiable fear and despondency on the other. It has been the writer's practice over many years to teach in considerable depth, including reference to fatalities, to senior aircrew during courses of instruction at Farnborough, leaving to them the assessment of the applicability of the risks in their own units. So far as junior aircrew and trainees are concerned, it is felt wise to restrict teaching to a simple enumeration of commoner symptoms and the basic treatment, namely descent.

There can be no substitute for clear and concise rules for handling of emergency situations where speedy and correct response is essential. To this end, the basic teaching should be that:

1)   Any person suffering from any symptoms at altitudes above 18,000 feet should, in the absence of clear evidence of acute hypoxia, be regarded as suffering from decompression sickness until proved otherwise.

2)   The only treatment is descent.

3)   Any person who has suffered from symptoms other than minor skin irritation or uncomplicated bends should be detained under competent medical care for at least four hours after descent.

4)   If a person is suffering from decompression sickness in an aircraft in circumstances in which immediate descent is impossible, he should ensure full oxygenation and adequate warmth, avoid exertion and recline or

lie flat. Where harness and seating arrangements prevent alteration of posture, if a person shows signs of loss of consciousness the aircraft should, if possible, periodically be inverted.

These four relatively simple golden rules should tell a pilot all that he needs to know for the handling of the acute incident. Their usefulness has been proved in practice.

Summary

Decompression sickness can be prevented by two means only; the avoidance of altitudes at which the condition is known to occur or by the elimination of nitrogen by pre-oxygenation.

In practice it is rarely possible to adopt either technique. However, selection and education can, if properly applied, reduce the risks of the occurrence of decompression sickness and its complications.

13

Sequelae

Introduction

Although no specific stress has been given to the point, it may have become apparent in the preceding chapters that one of the most striking features of subatmospheric decompression sickness is the rapid and complete recovery of the vast majority of cases. Admittedly, very exceptionally subjects enter a state of shock which may prove fatal, but there has been little mention of residual signs or symptoms. In the allied fields of compressed air and diving operations there is currently much concern over the question of sequelae and it is vital to investigate the possibility of permanent defects following ascent to altitude.

The best and most systematic way to investigate the problem is firstly to examine the available records for evidence of analogous conditions to those reported from high pressure work and secondly to survey the subsequent histories of known altitude cases.

Bone Lesions

The literature on bone lesions in compressed air workers and divers is now vast, dating from 1911. Fortunately it has been comprehensively reviewed (Fournier and Jullien, 1965; McCallum et al 1966). Briefly, lesions comprise areas of aseptic or ischaemic necrosis in the head and neck of the femur, the head of the humerus and less commonly, the lower end of the femur and the upper end of the tibia. There also arise infarcts in the medulla of the femur, the humerus and the tibia. Those near joint surfaces (juxta-articular lesions) often give rise to crippling deformity when the cartilaginous cap is distorted or fractured. The shaft lesions are rarely the source of pain or pathological fracture (Davidson, 1964B; McCallum et al, 1966). The overall incidence in some groups of tunnel and caisson workers may be as high as 17%.

The natural history of the disease is but poorly understood. Lesions may arise within a few months of exposure and a single decompression from high pressure may cause widespread damage (James, 1945). Cases have occurred with no history of acute symptoms of bends, but nevertheless have developed necrosis months or years later. There has been much discussion about the possible occurrence of similar changes following altitude exposure.

The most convincing case has recently been seen by the writer, having been initially detected by Dr E. J. Roebuck and Mr W. Waugh.

Case 28

A 43 year old photographic survey pilot had. over the past 20 years. been flying regularly in unpressurised aircraft at altitudes up to 28,000 feet for a total of about 1,000 hours. On one occasion in approximately 1955 he was working as a camera operator. He was very cold and soon after reaching 27,000 feet after a $1\frac{1}{2}$ hour climb, he began to experience severe pain in his fingers. knees. shoulders and elbows. The pain became excruciatingly severe but he managed to continue his duties for about 6 hours. He felt extremely ill on landing and was confined to bed with very severe pain in all limbs for 4 days subsequently.

On two occasions between 1963 and mid-1967 he had similar in-flight episodes lasting 6 hours. The severity of the pain was such on one occasion, that it took him almost 2 hours to extricate himself from the co-pilot's seat. On approximately six other flights he had moderately severe shoulder and elbow bends.

In May 1967 he was getting out of his car when he was aware of a sharp pain and an audible 'thunk' sound from his left shoulder. Radiographs revealed classical juxta-articular ischaemic necrosis and impending or actual separation of a fragment from the head of the humerus (Fig. 13-1). Six weeks later the pain was less intense but certain movements. especially extension and internal rotation resulted in a clearly-heard and felt jarring within the joint. Further x-ray films showed that separation of the fragment had occurred (Fig. 13-2).

The patient's other major joints and the shafts of the long bones appear radiologically normal. No abnormal haemoglobins were present in a blood sample and enquiry revealed no history of steroids other than in a single local injection into the joint on the occasion of the first examination. He had no exposure to compressed air and had carried out no diving.

The X-ray appearances are so typical that the diagnosis is felt to be certain. In particular, the shoulder joint is so rarely affected by idiopathic aseptic necrosis as to exclude this principal alternative diagnosis. The conditions of flight are extremely uncommon but exactly those which one would expect to be most liable to produce ischaemic damage i.e. prolonged maintenance of altitude in the presence of severe bends.

Pathogenesis

The pathogenesis of so-called caisson disease of bone has been generally attributed to bubbles within the circulation, but no detailed postulated mechanism has been forthcoming. This is due, no doubt, to the dearth of histological material and the failure of attempts to induce lesions in experimental animals. Gersh (1945) succeeded in demonstrating bubbles in the bone marrow of guinea pigs decompressed from high pressures and Colonna and Jones (1948) found similar evidence in rabbits, but neither paper contains any hint of a pathological picture analogous to that seen in human material. Averyanov and Mikhailov (1962) could not produce radiologically detectable lesions in dogs deliberately subjected to bends-producing decompressions.

Although there is little discussion of the findings in their published paper, the writer has been fortunate in being allowed to examine bone sections from the mice studied by Antopol et al (1964) of the Beth Israel Hospital, New York. The lesions in the femora are clearly massive infarcts and it is most interesting that they have been found in the thin, control mice as well as in the obese, susceptible mice.
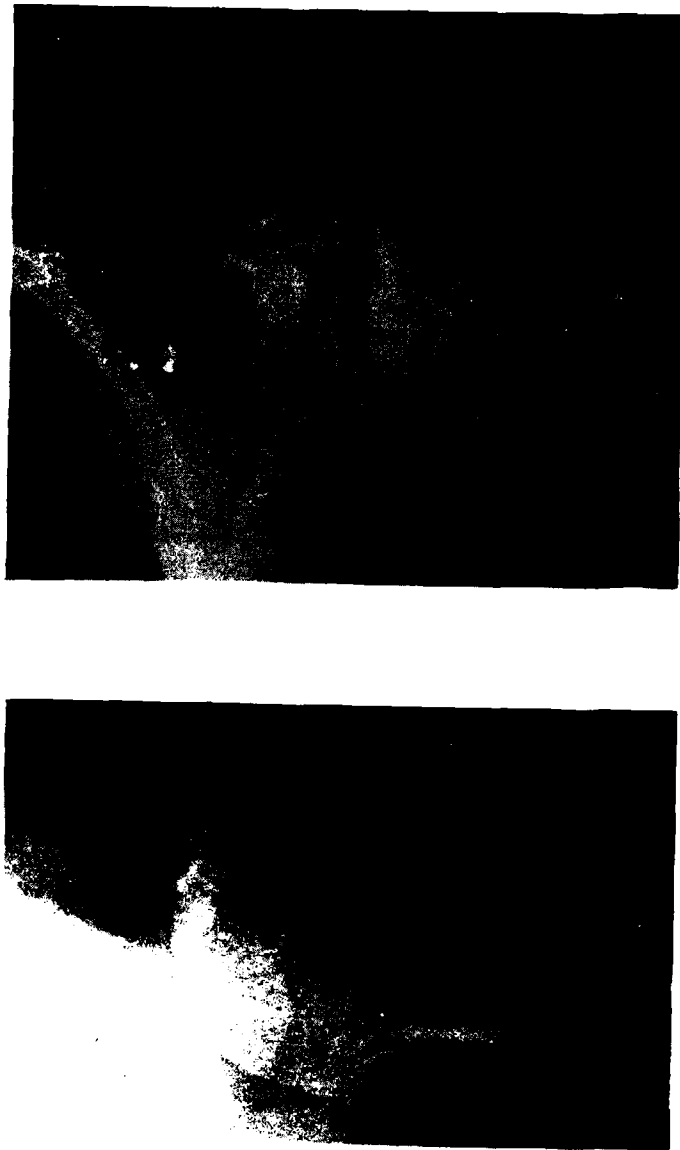
Fig. 13-1 Case 28. Radiographs of left shoulder A-P (top);
Axial (bottom), showing impending separation of
articular surface flake.
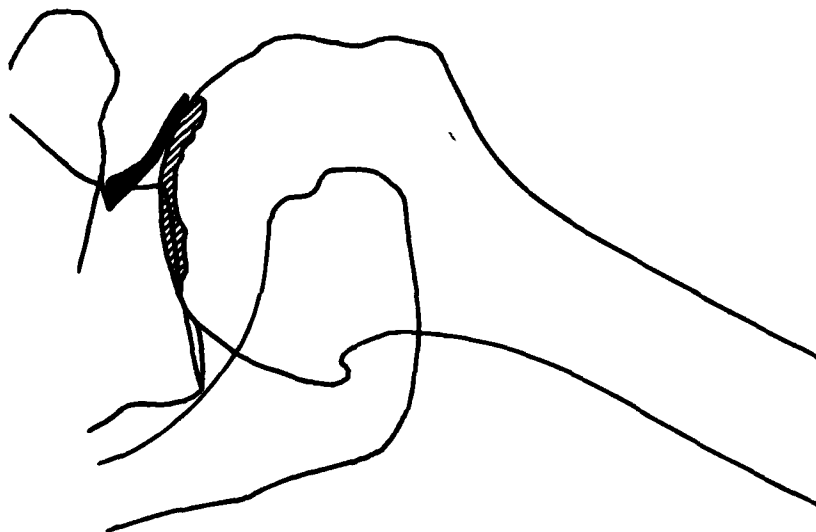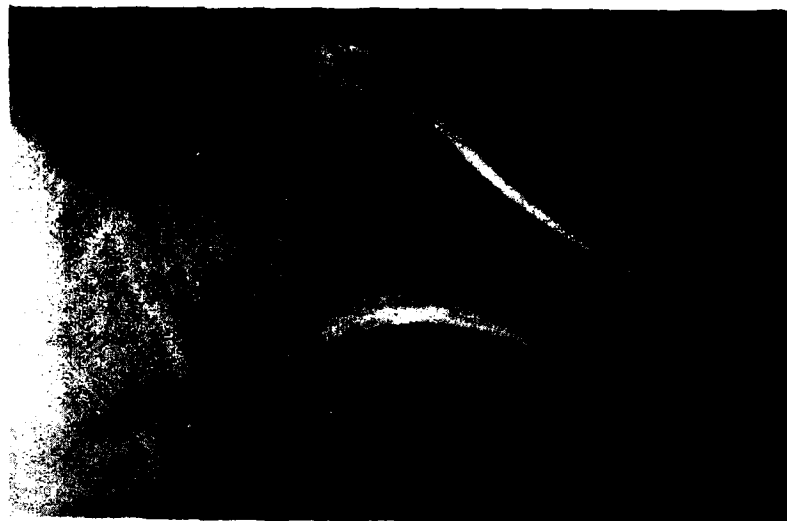
Fig. 13-2   Case 28.   Radiographs of left shoulder.   Axial view, taken 6 weeks after Figure 13-1.   Articular surface flake separated.

ZONE A — TOTAL INFARCT.
ZONE B — DENSE FIBROSIS.
ZONE C — REPAIR ZONE.
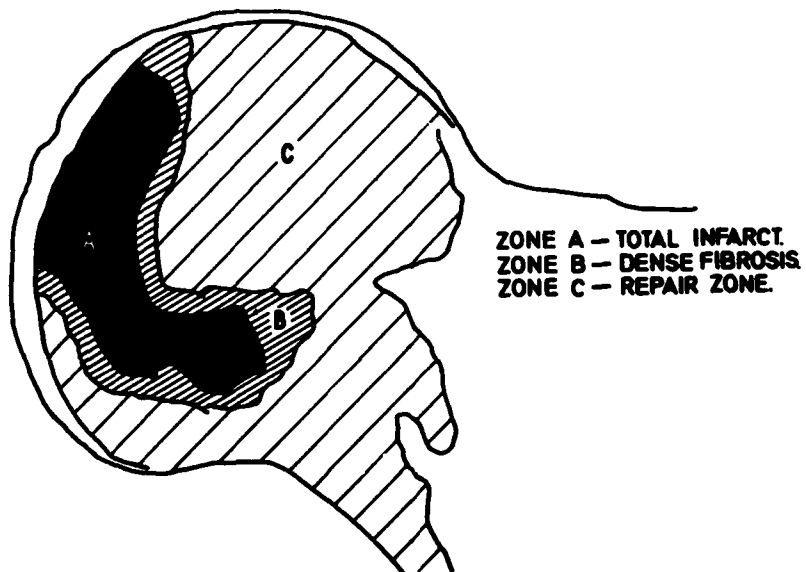
Fig. 13-3   Paraffin section and diagram of the head of the femur
of a compressed air worker, showing the characteristic
three zones of damage.
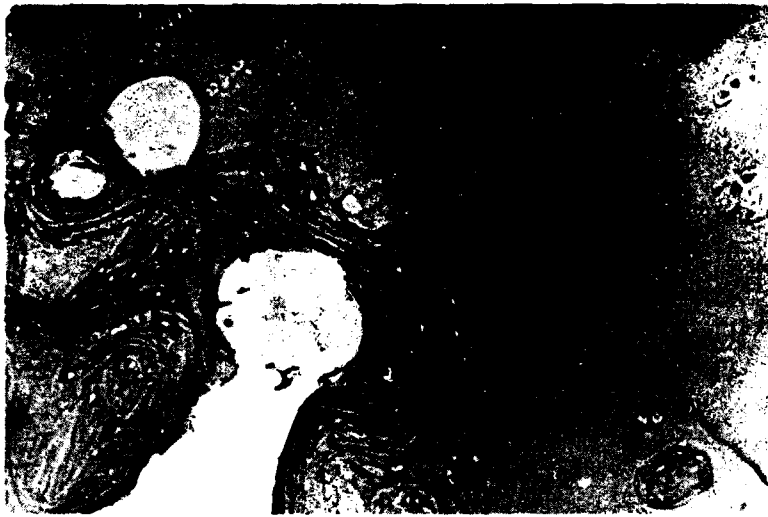
Fig. 13-4(a) Sub-articular area of Zone A in the section shown in
Figure 13-3, H. & E. x 130. From top right to
bottom left can be seen viable articular cartilage,
the line of calcification, dead cartilage and dead
trabeculae (no viable chondrocytes or osteocytes).

Fig. 13-4(b) Section from the junction between Zone B (right)
and Zone C (left) showing dead trabeculae, dense
collagen and on the extreme left, a lamina of live
bone and viable marrow. H. & E. x 130.
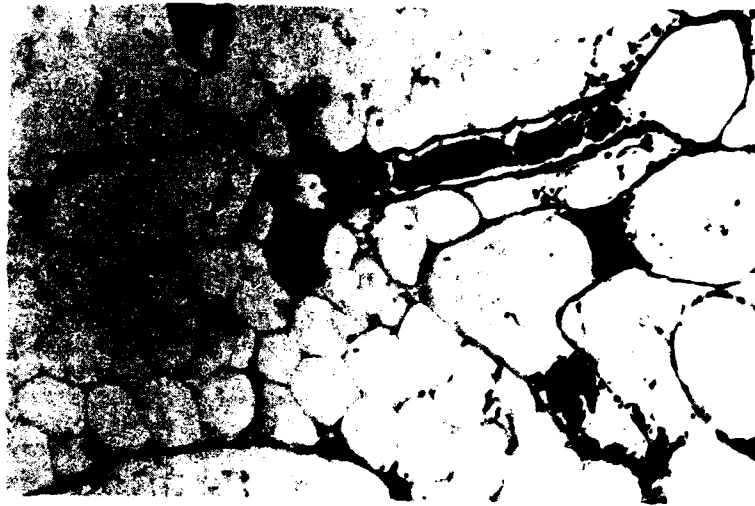
Fig. 13-5   Dilated venous channels in the medulla of the lower
end of the femur of a man who died shortly after a
routine decompression from an 8 hour shift in com-
pressed air.   Masson x 130.

Pathology

The early pathological reports (Kahlstrom, Burton and Phemister, 1939; Walker, 1940; Swain, 1942) were all of biopsy or necropsy-material in which the secondary changes of osteo-arthritis were pre-eminent. De Sèze et al (1963) also obtained material from two advanced cases, but in addition they secured the head and neck of the femur of a much less severe case who committed suicide nine years after lesions first became visible on radiographs. The findings in this material are of great interest in that they reveal that the process of infarction is much more wide-spread than the X-ray appearances would suggest.

An even earlier lesion has been studied by the writer in collaboration with Dr Mary Catto (Catto and Fryer, 1965; McCallum et al, 1966). A femur and the contra-lateral humerus were taken from a decompression sickness fatality (Bennison, Catto and Fryer, 1965). They showed no naked eye evidence of disease and minor changes only in slab radiographs, but striking ischaemic lesions in the heads of both bones and the shaft of the humerus were found in histological sections. For the purposes of this chapter it will suffice to describe briefly the appearances in the femoral head.

The primary lesion appears to be death of the major part of the head and neck of the femur (Fig. 13-3). Repair has been effected by laminar deposition of new bone (Zone C) on dead trabaculae, but the process appears to have become halted by an extremely dense fibrosis (Zone B). Enclosed deeply by this fibrous band and superficially by viable articular cartilage, is a totally dead region (Zone A). The cartilage is presumably nourished by oxygen diffusion from the synovial fluid, as is normally the case for this totally avascular tissue. Details of the pathological processes are shown in Figure 13-4.

Juxta-articular lesions commonly fracture through the dead trabeculae of Zone C and a fragment of cartilage and dead bone becomes a loose body within the joint space. Secondary fibrocartilage formation follows.

The underlying mechanism is not readily apparent. Arterial embolism would seem most improbable, in view of the conformation of the primary infarct. Certainly the lesion is not limited by the epiphyseal line. Thrombosis is nowhere evident and there is no suggestion of an inflammatory process. A possible mech-anism was suggested by the observation by Catto (personal communication) and the writer of widely distended venous channels in the femur and tibia of another decompression death, in whom there was no evidence of ischaemic bone damage (Fig. 13-5). Although dilated channels are sometimes seen in routine necropsy material, the beaded appearance and the degree of dilatation would suggest bubble agglomeration in these vessels of the medulla. It may be recalled that on page 59 the writer suggested that venous obstruction might be responsible for the pain of bends. It is also not unlikely that persistent obstruction of narrow cortical channels could cause venous infarction of the bone itself.

The fact that bone lesions and bends are both confined to the limbs would suggest that the aetiology of both might be related.

Differential Diagnosis

The differential diagnosis in a case with proven exposure to decompression is a matter of exclusion. The most common disease likely to cause confusion is osteoarthritis. The distinction between this condition and ischaemic necrosis is best made by observation of the joint-space in radiographs. In osteoarthritis, destruction of articular cartilage leads to narrowing and obliteration of this space, whereas in decompression sickness the cartilage is preserved.

Idiopathic infarction occurs occasionally in the hips (Serre and Simon, 1959A; d'Aubigné, 1964) but rarely in the humerus. Other causes of infarction include prolonged steroid therapy, sickle-cell trait and aplastic anaemia (Jackson, Pinkerton and Wilson, 1962). Serre and Simon (1959B) postulated an athero-sclerotic aetiology in one case of femoral infarction and Angei and Cossu (1955) have added endochondritis, parasitic lesions, osteomyelitis, cartilaginous degeneration and primary and secondary neoplasia to the list of possible confusing diagnoses. Shaft lesions are most likely to be confused with the common dense 'bone-islands' of unknown aetiology.

Occurrence in Subatmospheric Decompression Sickness

Allan in 1943, appears to have been the first person to look for bone necrosis in personnel exposed frequently to simulated altitude. He found no bone changes in three surveyed radiologically. Ratnoff, also in 1943, examined twenty-one colleagues at risk and found no unequivocal bone changes. Coburn (1956) reported in an abstract only, but later (1962) re-iterated his claims to have found eleven lesions in seven of forty observers and instructors regularly working in US Navy altitude chambers. Unfortunately he has not published illustrations. Berry and Hekhuis (1960) of the USAF were stimulated by Coburn's original report to examine 579 low-pressure chamber personnel and by contrast, they could find no evidence of bone lesions. Hodgson et al (1968) followed-up 164 of these men some six years after their original examination. They found nineteen unequivocal bone islands but two cases which they concluded to have definite decompression sickness-type ischaemic necrosis. One affected the neck of the humerus and another (missed in the original films) was a 4 cm long femoral shaft infarct.

Two post-flight cases have been claimed in the literature. Hodgson et al (1968) described a USAF case. An aircrew member suffered severe bends which persisted after descent twice within one week in 1953, when his B.29 aircraft suffered cabin pressurisation failure, once at 35,000 feet and on the other occasion at 43,000 feet. Subsequently he developed bilateral hip joint changes, necessitating medical retirement in 1962 and replacement of the femoral head with a prosthesis on one side in 1965. Less convincing is the case of Markham (1967) of a 45 year old diabetic who suffered stiff hips and later necrosis of both femoral heads in 1964. He gave a history of many prolonged high altitude flights during 1944 but no bends pain was ever experienced. The connection between the altitude exposure and the bone changes would appear rather tenuous and radiologically the hip changes could well be the idiopathic necrosis of d'Aubigné. Coincidence of this condition and a war-time history of high flying is not very improbable. To these must be added Case 28.

Complications

As has been discussed above, juxta-articular lesions may give rise to secondary joint changes should the head of the bone either collapse or undergo a shearing fracture just deep to the cartilage. Destruction can be very severe, particularly in the weight-bearing hip joint. Although surgical excision and replacement by prosthesis has been performed, the results have not always been favourable (McCallum et al, 1966). Arthrodesis for unilateral lesions has been considered. Another possible treatment is the boring of drill holes through the fibrous zone into the necrotic area and subsequent packing with autologous bone chips.

A hitherto unreported and most disquieting secondary change has recently been reported by Dorfman, Norman and Wolff (1966). Shaft lesions have always been regarded as silent, virtually hall marks of the compressed-air worker's trade, for they never appear to involve the cortex and thus do not weaken the bone significantly. However, in the case cited by Dorfman, Norman and Wolff, a 64 year

old caisson worker with a known femoral shaft lesion of least fourteen years'duration, developed an anaplastic fibrosarcoma at the site of the infarct. This neoplastic change within an infarcted area of bone is not unknown in local bone necrosis from other causes, but this is believed to be the first such case arising in a decompression-caused lesion.

Neurological Sequelae

Severe compressed air and diving forms of decompression sickness include a high proportion of cases of neurological damage, many of which are permanent if not treated promptly and adequately. Most typical is a cord lesion giving rise to spastic or flaccid paralysis of the lower limbs, retention of urine and incontinence of faeces.

Aviation Cases

Quite remarkably rare are neurological sequelae of decompression sickness arising at altitude.

In British experience there has been only one case of neurological sequelae. He has already been referred to briefly on page 130.

Case 29

A 28 year old flight test observer was flying in a large unpressurised prototype aircraft in June 1950. For 2 hours the aircraft flew at 7,000 feet and then climbed slowly, over 70 minutes, to 25,000 feet. Within 15 minutes this man complained of feeling ill and hot. Almost immediately he gripped the side of his seat and lost consciousness. He was carried aft, receiving oxygen the whole time. Within 15 minutes the aircraft had been brought to 10,000 feet, where he opened his eyes and moved a little. Generally he was pale, sweaty and completely limp, although he occasionally drew up his legs. The aircraft landed 50 minutes later. During the next 8 days he remained in a comatose state, developing a spastic quadriplegia.

Two months later he had stiffness of the left arm and some loss of sensitivity of the left hand. Both legs were mildly spastic, with extensor plantar responses and some ataxia of the right leg. He had an almost complete lack of knowledge of the position of his right leg, attributed by a neurologist to a disturbance of body image resulting from a cortical lesion. He also had a small area of scarring of the left retina. Seventeen years after the original incident he still has some numbness of the left arm and the lower limbs and trunk below the waist. This sensory loss is aggravated by fatigue. He has slight spasticity of the left arm and both legs.

A somewhat similar case of residual paresis, in this case of one leg, has been reported by Höök, from Sweden (Höök, 1958).

Less clear cut are psychosomatic syndromes arising from acute episodes of decompression sickness. Mebane (1955) was the first to draw attention to such a case. A pilot having experienced acute decompression sickness after losing cabin pressure at 38,000 feet had, over a period of months, many attacks of feeling out of touch and very anxious. He was found to have a unilateral choroidal lesion with a corresponding visual defect and also a constriction of the colour field in both eyes.

Berry (1960) reported an in-flight case who had, seventeen months later weakness and inco-ordination of the left arm and right leg, memory and speech defects and easy fatigability.

Lisk, Crowley and Lewis (1967) could find records of two cases of residual neurological lesions in the USAF.

In the RAF there have been two cases of possible psychosomatic or psychiatric responses to decompression sickness.

Case 30

A 33 year old navigator with very little experience at high altitude, was in a Canberra aircraft in July 1958 on a long distance navigation exercise. After 3 hours at a cabin altitude of 26,000 feet, he noticed a strange transient tingling sensation in the front of his chest on the right side. Twenty minutes later he developed abdominal pain and a frontal headache. Movement gave rise to acute vertigo and he became clumsy and his speech was slurred. He was clammy and distressed by a persistent cough. When his seat harness was undone and he was placed on the aircraft floor, he felt much better. He never lost consciousness.

The aircraft was landed some 1 hour 20 minutes after the onset of symptoms. He had a residual headache, cough and fatigue. He slept soundly for 2 hours and was then flown home at low altitude. Ten hours after the original departure he landed back at base. He was normal on clinical examination but a blood sample revealed a haemoglobin level of 120%.

Apart from feeling easily tired for a few days he made a full recovery. However his mental powers began to decline and he developed a gross exaggeration of his original personality. He became labile, irritable and tearful. His powers of concentration waned and he had difficulty in recalling messages and names. Letters and books became hard to comprehend. He showed marked irresponsibility in financial matters but showed little concern over the results. Not surprisingly his matrimonial affairs became rather unsettled and *post hoc* or *propter hoc* he took to occasional bouts of drinking.

When seen 4 years after the original incident he was noticeably euphoric although in possession of full insight. He was discharged from the service as no longer suitable for employment in his aircrew role. It was impossible to decide whether the psychic trauma of the original in-flight incident or organic lesions of the cerebral hemispheres had given rise to this sudden exaggeration of pre-existing personality traits, to the point of frank behavioural defect.

Case 31

A healthy young man trained as a pilot in 1952 and subsequently had 3 years uneventful career as a fighter pilot. In 1955 during the course of a decompression test, which followed immediately upon a hypoxia demonstration, he developed foveal blurring, headache and bends in several joints. In spite of instructions to the contrary, he continued to fly to 37,000 feet in unpressurised aircraft, often experiencing bends.

After a tour of ground duties, in 1961 he returned to flying. In the course of both of two decompression tests at 28,000 feet he had symptoms. In the first he had bends, blurred vision, itching and post-descent nausea and vomiting. After the second, 2 days later he had bends and slight visual blurring. After descent he developed a temporary disturbance of vision in the right eye.

After the second, 2 days later he had bends and light visual blurring. After descent he developed a temporary disturbance of vision in the right eye.

He was restricted thereafter to ground duties but he began to complain of frequent attacks of headache and eye strain, aggravated by an attempt to train him as a photographic interpreter. He was then taught to fly helicopters, but developed migraine attacks at increasingly frequent intervals, culminating in an accident attributable to such an attack occurring in flight. He was discharged in 1965 with a diagnosis of migraine and height sensitivity.

In 1966 he entered into protracted correspondence with various authorities, for, in spite of a declared history in 1964 of "migraine all his life", he attributed the onset of all his troubles to his decompression tests and wrote of "joint pains, locking of limbs, loss of vision in one or both eyes and large patches of sore and tender skin".

His fixation on decompression tests as the origin of a wide range of ills is difficult to assess. Thorough neurological examination by an independent assessor failed to reveal any evidence of organic disease. It is felt that, like the previous case, his history is one of exaggerated personality traits after a series of altitude incidents.

Pathogenesis

In Western literature there is no reference to diffuse cerebral or cerebellar defects in decompression sickness following exposure to compressed air. However, from Hungary has come a series of papers on this topic (Rózsahegyi and Soós, 1956; Rózsahegyi, 1959; Rózsahegyi and Roth, 1966). The Budapest industrial health authorities have followed over one hundred men with claimed neurological defect after working on the construction of tunnels for the local underground railway system. Complex neuropsychiatric disorders have been diagnosed, including 'pseudo-Méniere's disease', 'vegetative neurosis', hysterical personality, anorexia, sleep disorders, dermatographia, impotence and pathological drunkenness. A high proportion were claimed by Rózsahegyi and Roth to show EEG abnormalities and they assumed the cause to be widespread focal embolic lesions.

Special Senses

The Eye

Apart from the case of Mebane (1955) no case of permanent visual disturbance has been reported in the aviation literature, nor have the other special senses been recorded as subject to residual damage.

From the compressed air work in Budapest, Imre (1962) has reported a case of advanced retinopathy believed due to arterial embolism. In a survey of thirty-six other compressed air workers, this author claimed to find eighteen cases of abnormal retinal appearances including haemorrhages, pigmented lesions, gliosis and tortuosity of the vessels.

The Inner Ear

Laba (1963) has reported from Poland that divers may show extra-cochlear deafness after neurological forms of decompression sickness and Rózsahegyi and Roth (1966) have written of vestibular disorders. Neither has been reported in the aviation literature.

The Cardiovascular System

The ECG

Rózsahegyi and Kenedi (1961) have studied the ECGs of 308 caisson workers and claim to have detected over twice as many abnormal records as in a matched group of 300 non-compressed air workers. They write of altered P-waves, lengthened PQ intervals, shallow T waves and sinus arrhythmia. No equivalent changes have been reported in altitude cases.

The Peripheral Blood

Zambrano, Mazza and Anzano (1954) have reported low plasma protein levels, lowered potassium and raised sodium concentrations and eosinophilopenia in twelve caisson workers. Again, no evidence exists of such changes in aviators.

The Pulmonary Circulation

Barnard (1957) appears to have been the discoverer of a most interesting pheno-menon. He found that rabbits given increasing daily intravenous injections of oxygen, nitrogen or argon (starting at 0.1 ml/kg, rising by 0.05 ml/kg every fourth day) for thirty to one hundred and twenty days developed profound pulmonary arterial damage. Regardless of the gas used or the period of administration (i.e. 30 to 120 days), most showed arteritis, intimal fibrosis and massive medial hypertrophy of small and medium-sized pulmonary arteries.

Wright (1962) injected air intravenously on alternate days in rabbits (0.5 to 1.5 ml/kg) for two to ten months. In two weeks arteritis was obvious, followed by pro-liferative endothelial and medial lesions. By ten months degenerative changes be-came apparent and right ventricular hypertrophy was marked. The lesions closely resembled those of pulmonary hypertension in man. Animals allowed to live for a further three months with no further air injections most surprisingly showed regres-sion of all lesions.

Boerema (1965) followed the early stages of damage in rabbits given 0.5 ml of air or oxygen per kg. daily into an ear vein for from one to sixty-five days. Others were left for periods of up to one year after such courses of injections, whilst controls were subjected to ear vein puncture only. Acute pulmonary arteritis could be detected after three days of injections of air or oxygen and after five days the lesions, comprising periarterial and medial inflammation and endothelial pro-liferation, were so advanced as to appear virtually obliterative. Intimal fibrosis followed with elastic lamina damage, but medial hypertrophy was not mentioned. All the lesions were completely reversible, normal appearances being restored within a few months, but for some residual sub-endothelial fibrosis.

Since pulmonary gaseous embolism is the most generally accepted basic pheno-menon in decompression sickness, it is important to seek similar pulmonary changes in men exposed to compressed air or to altitude, although it should be noted that all the reports of induced lesions in animals have been on the same species, the rabbit.

In the lung sections from the reported human altitude fatalities, no such changes have been seen, in spite of careful examination (see Chapter 8). Similarly, in the compressed air fatalities reported by Sillery (1958) and by Bennison, Catto and Fryer (1965), the lungs showed no arterial lesions. In contrast, an unpub-lished case seen by the writer in 1963 showed the most strikingly advanced lesions.
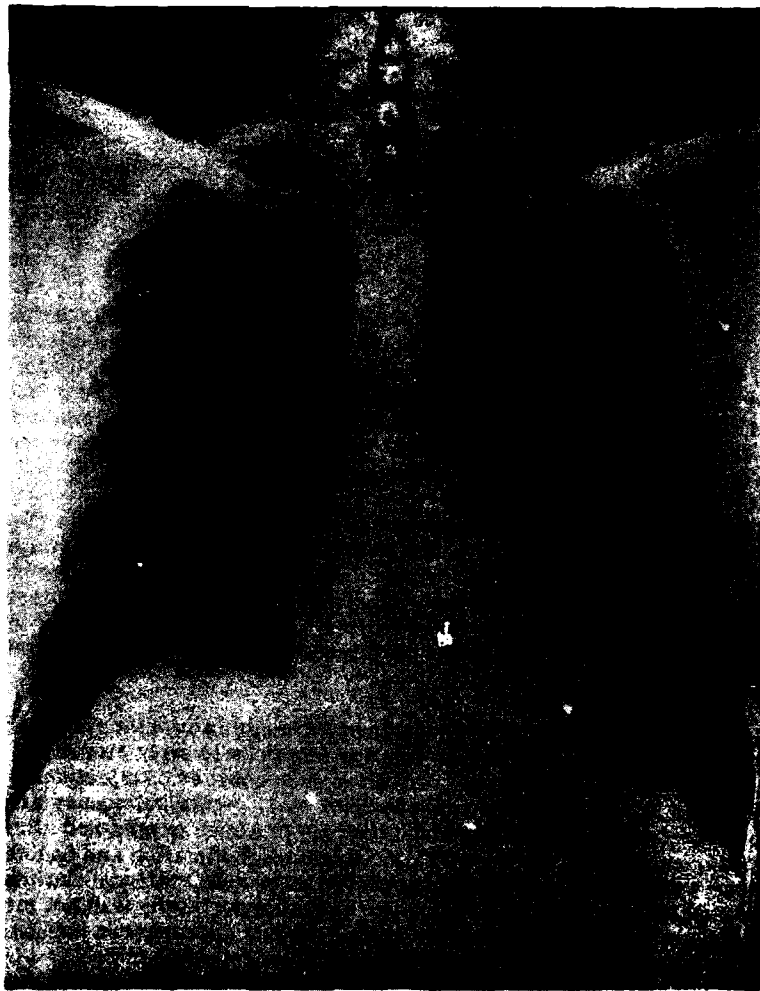
Fig. 13-6   P.A. Radiograph of the chest of Case 32, taken 7 months
before the fatal incident.

(a) (b)
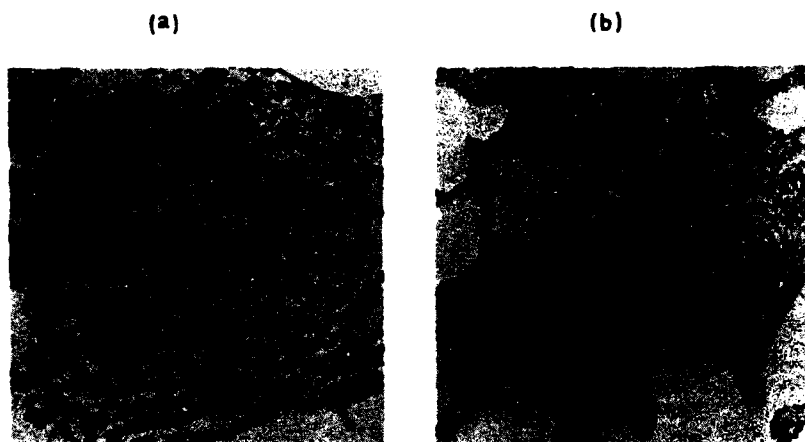
Fig. 13-7 a and b Pulmonary vessels of Case 32, showing arteritis,
endothelial proliferation and medial hypertrophy.
H. & E. (a) x 195, (b) x 95.

(c) (d)
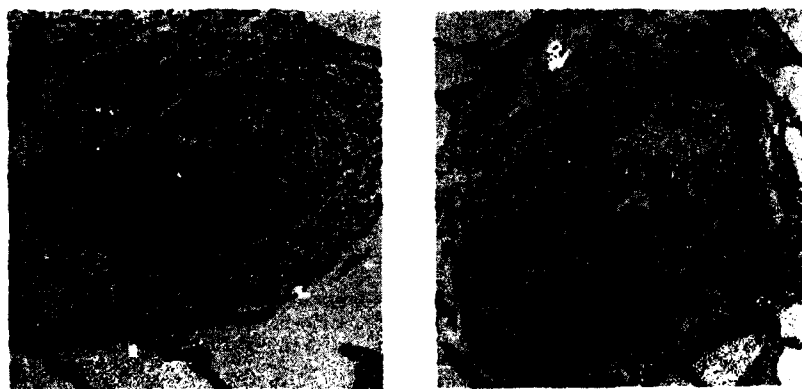
Fig. 13-7 c and d Pulmonary vessels of Case 32, showing arteritis,
endothelial proliferation and medial hypertrophy.
H. & E. (c) x 95, (d) x 65.

Case 32

A well built man of 25 was employed as a tunnel face worker for almost 3 years. His health was excellent but he was surprised in March 1963 when he was referred to the site doctor because a radiologist queried the shape and size of his heart on a routine chest x-ray film (Fig. 13-6). There was no clinically detectable abnormality in his heart or chest and he countered any question of debility by carrying out ascent and descent of a 100 foot ladder twice in quick succession, without resultant dyspnoea.

Seven months later he awoke in the night, having felt fully fit all day and having completed a full 8 hour spell at the working face, with a tight feeling in his chest and fever. He felt generally unwell and next morning called on his general practitioner who, hearing moist sounds locally in the right chest just below the angle of the scapula, diagnosed pneumonitis and prescribed terramycin. Within 24 hours he responded to the extent of feeling full fit, but he was quite correctly instructed to remain away from work until a total of 7 days had elapsed.

A further 7 days after returning to compressed air work he demonstrated his conscientiousness with regard to regulations by insisting on a repeat decompression because, although he felt no ill effects, there had been a minor irregularity in his routine decompression in that the last 2lb/sq. in. of pressure was lost abruptly owing to a door-seal fault.

On the following day he completed, without complaint, a routine 8 hour shift at the face of the boring under a pressure of 37 to 40 lb/sq. in. (gauge). He was decompressed in accordance with the 1958 regulations for Work in Compressed Air (Ministry of Labour, 1958) and in deference to regulations he remained in the vicinity of the decompression lock for an hour. He then set off, driving his car, dropping a passenger 3 miles from the site. This colleague thought that his friend was behaving slightly unusually "as though a bit high". He drove himself home, a further 26 miles, without untoward incident, but was found by his wife, sitting in the driving seat, confused, incoherent and unable to extricate himself from the car. He was helped into the house where he collapsed, dyspnoeic and frothing at the lips and he died almost immediately, 2 hours 35 minutes after leaving the decompression lock.

At necropsy the only abnormal findings were a pint of straw-coloured fluid in each pleural cavity and some pulmonary oedema. His heart weighed 420 gm, slightly heavy for his build, the valves and main vessels were normal and the only detected abnormality was a patch of a few petechiae on the interior of the left ventricle. There was some froth in the pulmonary artery.

Histologically there were no abnormal findings in any organ except the lungs. In particular, a full neuropathological examination of the brain was reported as revealing no abnormality whatsoever. There were neither fatty liver nor fat embolism.

The lungs were the site of an astounding degree of arteritis with masses of eosinophils and neutrophils in the walls and the adventitia of almost all the small vessels (Fig. 13-7a and 13-7b). Many arteries had apparently been completely occluded by endothelial proliferation and had been re-canalised (Fig. 13-7c). Larger vessels were the site of massive medial hypertrophy (Fig. 13-7d). The changes were virtually indistinguishable, apart from the predominance of eosinophils, from the illustrations of Boerema's rabbits subjected to repeated air embolism (Boerema, 1965). The comments of a very experienced pulmonary pathologist were that

in the absence of the history, he would have stated with confidence from the histological appearances that this man had been a bed-ridden cardiac cripple for many months before his death.

In the absence of any family history of idiopathic pulmonary hypertension and in view of the completely clear past history, it is tempting to attribute the changes in this man's lungs to repeated gaseous embolism. The short interval (15 days) between his 'pneumonitis' and his death, together with the suggestion of cardiac hypertrophy on radiological examination seven months earlier, makes it unlikely that the infective episode played a significant part in the development of the overall picture of pulmonary vascular disease.

How else could one explain the condition? On the other hand, why have such appearances not been found in other deaths associated with compressed air or for that matter, with aviation? Clearly individual hyper-susceptibility can be the only explanation. It is notable that in the early stages there was considerable variation between different rabbits in Barnard's series (Barnard, 1957).

Prospective Studies

In case sequelae might be missed, the writer has taken the opportunity provided by service documentation to follow up 109 cases in addition to those referred to already in this chapter. Since aircrew are examined annually and are required to have a very high standard of physical and mental fitness, deviations from normal should be readily detectable. Follow-up is possible until a man leaves the service. Table 13-1 shows the result of the survey.

Of the 109, seven were killed in flying accidents, none in circumstances in which decompression sickness could be suspected as a cause of loss of control. Six men had histories of psychiatric disturbances, all quite mild. Two anxiety states were clearly related to the operating role; none was related to or dated from the decompression incident. Of more serious conditions there were only four cases. One man nine years later had moderately severe perceptive deafness, one developed Parkinsonism, one lichen planus of the lips and one osteoarthritis. The latter is the only case in which a suspicion of a relationship could be raised. This man has already been referred to as Case 7 (page 72); he had severe symptoms during a prolonged flight at 18,500 feet. Nine years later he developed arthritis in both hips and his disability became quite severe by the time that he was discharged, with a pension and a diagnosis of osteoarthritis of both hips. The radiographic appearances of his joints are unlike those of decompression sickness and he had three features in his history which point to osteoarthritis as the correct diagnosis. He was very severely overweight, he had a history of hip injury during a heavy parachute landing and he had chronic osteomyelitis of the femur as an outcome of a crack fracture of the femur on that occasion.

Summary

Sequelae to subatmospheric decompression sickness are extremely rare, particularly in comparison with the long-term effects of work in compressed air.

Neurological defects with clear-cut physical signs total four or five only, to which must be added two personality changes most likely to be latent defects brought out by the psychological and physical trauma of a severe decompression incident.

No evidence of other sequelae has been found in a substantial survey of cases, over periods of up to fifteen years.

Table 13-1   Follow-up data

Period of follow-up (years)	Number
Less than 1	16
1-2	8
2-3	7
3-4	14
4-5	7
5-6	10
6-7	8
7-8	8
8-9	11
9-10	3
10-11	1
11-12	0
12-13	6
13-14	9
14-15	1
	109

Animal work might suggest that pulmonary lesions could arise if gaseous embolism results from ascent. A single case only has been detected and this in a compressed air worker, but the changes so strikingly resemble those recorded in animals that an individual sensitivity might be invoked.

Follow-up should become an established part of the management of cases of severe decompression sickness.

14

Conclusions

There can be few subjects as frustrating as that of subatmospheric decompression sickness, for its manifestations are so protean, its mechanisms so obscure and its prevention so difficult in practice, that the practitioner's role is largely that of a collector of data. Particularly unfortunate is the lack of success in attempts to produce an analogous condition in experimental animals.

The main advance in recent years has been the advent of high-pressure therapy, with the result that hitherto irreversible shock cases have become recoverable.

In any air service, military or civilian, routine or research, there would appear to be an element of risk and so long as that risk exists it is essential that the aviation medicine specialty should be alert for incidents. As a result of intensive study the mortality of decompression testing would appear to have fallen, since severe cases have been more readily anticipated and shock has been actively treated. In-flight hazards can only be dealt with if they are recognised. To that end education is vital. Doctors working with aviators must learn as much as possible about decompression sickness, how to alleviate the symptoms, how to reduce the hazards and what steps to take should they encounter a case. Finally, concise and up to date information must be made available to clinicians who might become responsible for the hospital treatment of victims.

Ever since pressurised cabins were first introduced the hazards of decompression sickness have been claimed to be almost beaten, but history has proved the optimists wrong. Ageing aircrew, extended flight durations, an overall increase of certain types of high flying, the emergence of the sport of skin diving and finally the achievement of space flight - all have served to keep alive interest in this subject and to keep going a steady flow of enquiries from designers and operators to aviation medicine laboratories.

Aviation has many many risks and a proportion of these would appear to be regarded as acceptable. Decompression sickness as a source of discomfort will always be with us as long as aircraft fly high and mechanical systems prove susceptible to defects. Decompression sickness as a source of severe distress, permanent damage or death is an unacceptable hazard and the medical profession must hold itself responsible for a proportion of such incidents, since they all too often result from poor education of aircrew, inadequate supervision, lack of advice to designers and operators and a failure of vigilance.

The elimination of decompression sickness as an aviation hazard is an exciting challenge and one which is clearly and correctly the responsibility of that element of the medical profession which works closely with the aviation industry and the military and civilian flying organisations.

Appendix

The High Altitude Selection Test

Introduction

The form of test under consideration was introduced in April 1954. The test comprised ascent at 5,000 ft/min. to 28,000 feet, maintenance of that altitude for two hours, followed by descent at 5,000 ft/min, to 20,000 feet and 3,000 ft/min. from 20,000 feet to ground level. The test was carried out twice at an interval of not less than forty-eight hours and not more than thirty days.

The criteria for pass and fail categories were clearly defined when the test was designed, symptoms being categorised as mild, moderate and severe. The latter classification should be used for all symptoms causing premature descent. Mild symptoms on two runs or moderate symptoms on one were acceptable, whereas mild symptoms on one run and moderate symptoms on a second, moderate symptoms on two occasions or severe symptoms on any occasion lead to failure of the candidate.

In practice, the test was not applied with scrupulous attention to detail. Occasionally the criteria for pass and fail seem to have been interpreted incorrectly and third runs were sometimes used for purposes of clearing an individual. However, the data available from this survey constitute a very large number of exposures of men to an altitude rarely selected in the past and therefore detailed analysis is indicated.

The Sample

This survey covered the results of 4,956 exposures of 2,606 men. It proved an extremely difficult and time-consuming task to analyse all the data in all respects and therefore, for some purposes a random sample of 806 cards was taken and the results of analysis extrapolated to give an indication of the nature of the whole group.

The Rate of Ascent

Ten rates of ascent were recorded, varying from 2,000 ft/min. to 5,000 ft/min. and including combinations of one rate to 20,000 feet, followed by a lower or higher rate from 20,000 to 28,000 feet. From a large sample it is estimated that the rates occurred with a given frequency, see Table A-1.

Table A-1   Ascent rates

2,000 ft/min.	0.4%
3,000 ft/min.	7.8%
3,000 ft/min. to 20,000 feet, then 2,000 ft/min.	11.2%
4,000 ft/min.	0.6%
4,000 ft/min. to 20,000 feet, then 2,000 ft/min.	0.6%
4,000 ft/min. to 20,000 feet, then 3,000 ft/min.	27.1%
5,000 ft/min.	4.2%
5,000 ft/min. to 20,000 feet, then 3,000 ft/min.	0.8%
Other or unknown rates	0.5%
	100.0

Table A-2   Numbers of runs per individual

One run only	344
Two runs	2,199
Three runs	39
Four runs	23
Five runs	1
	2,606

Individuals Exposed

The 4,956 exposures were experienced by 2,606 individuals. Of these, the mult-
iple exposures were made up as shown in Table A-2. Multiple runs were not neces-
sarily made by an individual within a short period, therefore it was not possible to
give an age to some persons because, for example, a man who had four runs may
have had two at age 26 and two at age 29. It was necessary therefore for the pur-
pose of analysis to devise a suitable method of assessment in order to study the
effects of age, weight, etc. For this purpose runs were grouped as single, double
or treble. They were defined as follows:-

> (a) A single run comprised of an isolated decompression to 28,000 feet for
> two hours or until descent was indicated by symptoms, with no similar exposure
> within two months either prior or subsequently.

> (b) A double run comprised of two such exposures of one individual.
> Although the statutory period was not more than thirty days between runs, in
> order to include those exceptional cases of slight exceeding of the interval,
> a period of two months was used in this analysis.

> (c) A treble run comprised of three exposures of an individual with not
> more than one month between first and second or second and third, i.e. with-
> in two months.

On this basis the example quoted above would be classed as two double runs, one for
an individual aged 26, another for an individual aged 29. This manipulation of the
data affected a very small proportion of multiple runs, less than 1.0%.

For other purposes, the category man/run was used, i.e. actual exposures.
Analysis of this category must be made with care, since second exposure of suscep-
tibles is not necessarily comparable with second exposure of non-susceptibles.

Susceptibility to Decompression Sickness - General

Of the 2,606 persons tested, 141 suffered on one or more occasions from some form
of decompression sickness. This gave an attack rate or morbidity of 5.41%.
Forced descent was necessary on account of symptoms and/or signs of decompres-
sion sickness for thirty-eight individuals, comprising 1.46%. Two individuals were cate-
gorised failed and subsequently re-categorised passed. The failure rate, as
assessed by actual action taken by the units concerned, was of the order of 1.2%.
Text-book application of the regulations should have led to the failure of forty-five, with
subsequent re-testing and passing of two. This would give a failure rate of 1.65%.
The 414 persons affected included fifty-four pilots, seventy-four navigators, seven
other aircrew and six non-aircrew men.

One run only was completed by fourteen of the personnel who developed symptoms. In
eleven of these the symptoms were such as to contra-indicate a second exposure. In the
remaining three, no reason can be ascertained for the failure to submit themselves
for a second test, although it is to be expected that withdrawal from flying for other
reasons, or posting may account for one or more.

One hundred and seven men experienced symptoms in one or both of two runs. The
actual figures were:-

Table A-3   Analysis of run on which symptoms were reported in 'doubles'.

Symptoms on first run only	47
Symptoms on second run only	47
Symptoms on both runs	13

Seventeen men were decompressed three times, eight as triple runs, nine having a double run and on a different occasion, a single run.   Their symptoms occurred as follows:

Table A-4   Analysis of runs on which symptoms occurred in three exposures.

Symptoms on first run only	7
Symptoms on second run only	0
Symptoms on third run only	3
Symptoms on first and second runs	2
Symptoms on first and third runs	3
Symptoms on second and third runs	1
Symptoms on all three runs	1

Three men were subjected to double runs on separate occasions;   one suffered from mild symptoms on the second run only, one from symptoms on both runs of the second pair and one on both of the first pair and the first run of the second pair.

1.0

4.5
5.0
5.6

2.8

2.5

3.2

2.2

3.6

1.1

4.0

2.0

1.8

1.25

1.4

1.6
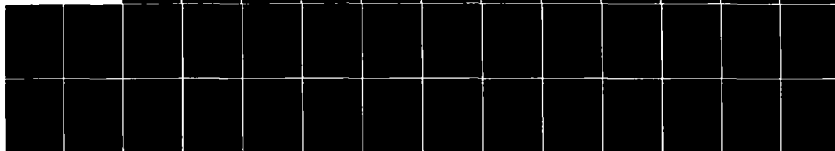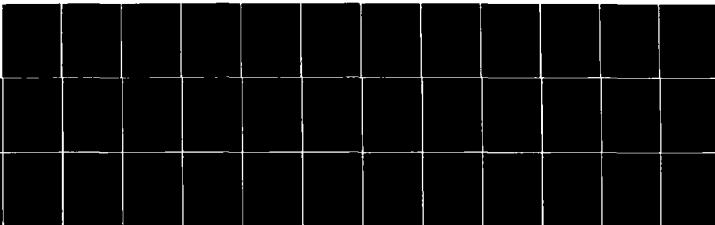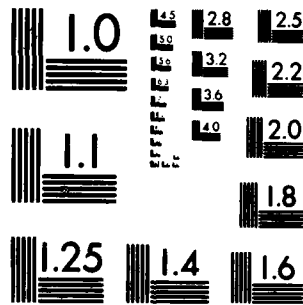
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

References

Abbott, W.E., Krieger, H. & Levey, S., 1955. 'The role of ACTH, Cortisone and Hydrocortisone in surgery'. Ann. Intern. Med., 43, 702-730.

Ackerknecht, E.H., 1944. 'Paul Bert's triumph'. Bull. Hist. Med., Suppl. 4, 16-31.

Adams, B.H., 1931. 'Observations on submarine lung training'. Nav. Med. Bull., 29, 370-372.

Adams, B.H. & Polak, I.B., 1933. 'Traumatic lung lesions produced in dogs by simulating submarine escape'. Nav. Med. Bull., 31, 18-20.

Adams, J.E., Owens, G., Mann, G., Hendrick, J.R., Munoz, A. & Scott, H.W., 1959. 'Experimental evaluation of Pluronic F68 (a non-ionic detergent) as a method of diminishing systemic fat emboli resulting from prolonged cardiopulmonary by-pass'. Surg. Forum, 10, 585-589.

Adams, J.H., Brierley, J.B., Connor, R.C.R. & Treip, C.S., 1966. 'The effects of systemic hypotension upon the human brain. Clinical and neuropathological observations in 11 cases'. Brain, 89, 235-268.

Adebahr, G., 1960. 'Anatomischer nachweis der Luftembolie in Herzblut'. Zentbl. allg. Path. path. Anat., 101, 347-351.

Adler, H.F., 1950. 'Neurocirculatory collapse at altitude'. USAF School of Aviat. Med., un-numbered report.

Aladjemoff, L., Weinberg, H. & Alkalay, I., 1963. 'Fat embolism. Treatment with lytic cocktail and surface cooling'. Lancet, (ii), 13-15.

Aleksandrov, A.I. & Brestkin, A.P., 1964. 'The permissible supersaturation coefficients in human beings breathing air and a helium-oxygen mixture'. In Brestkin, M.P. (Ed.), 5-9.

Alexander, F. & Macdonald, D.C., 1960. 'The action of carbon tetrachloride on the sheep's liver'. Q. Jl. Exp. Physiol., 45, 12-17.

Alexander, G.L., 1960. 'Diagnosis of fat-embolism'. (letter), Lancet, (ii), 986.

Allan, J.H., 1943. 'Decompression disease of bone'. J. Aviat. Med., 14, 105-111.

Allan, J.H., 1945. 'Traumatic calcification: a precipitating factor in bends pain'. J. Aviat. Med., 16, 235-242.

Andersen, H. R., 1965. 'A historical review of the bubble theory of the etiology of decompression sickness as related to high altitude exposure'. USAF School of Aerospace Med., Aeromed. Rev. 10-65, 40pp.

Anderson, R.M., Fritz, J.M. & O'Hare, J.E., 1965. 'Pulmonary air emboli during cardiac surgery'. J. thorac. cardiovasc. Surg., 49, 440-449.

Angei, A. & Cossu, R., 1955. 'Infarto osseo: contributo clinico-radiologico'. Archo Radiol., 3, 3-13.

Anon., 1930. 'A fatal case of caisson disease following a dive of short duration to a depth of thirty feet'. Nav. Med. Bull., 28, 862-865.

Anon., 1936. 'The new altitude record. Medical aspects of stratosphere flying'. Br. Med. J. (ii), 731.

Anon, (US Navy). 1943. 'The effects of flight - physical and mental aspects'. Published under supervision of Trng Div. of Bur. Aeronaut., USN. New York, McGraw Hill. pp. 125.

Anon., 1955. 'Clinico pathologic conference. Decompression sickness'. U.S. Arm. Forces Med. J., 6, 1787-1799.

Anon., 1962. 'Case records of the Massachusetts General Hospital. Weekly clinicopathological exercise - case 48 - 1962'. New Engl. J. Med., 267, 200-206.

Anthony, R.A., Clarke, R.W., Liberman, A., Nims, L.F., Tepperman, J. & Wesley, S.M., 1943. 'Temperature and decompression sickness'. U.S. Natn. Res. Coun., Comm. Aviat. Med., Report 136.

Antopol, W., Kalberer, J., Kooperstein, S., Sugaar, S. & Chryssanthou, C., 1964. 'Studies on dysbarism. I. Development of decompression syndrome in genetically obese mice'. Am. J. Path., 45, 115-127.

Armstrong, H.G., 1939. 'Principles and practice of aviation medicine'. London, Baillière, Tindall & Cox. pp. 496.

Armstrong, H.G. & Borum, F.S., 1938. 'The development of caisson's disease at high altitude'. U.S. Army Air Corps, Wright Field, Engng. Sect. Memo. Report Q-54-59.

Armstrong, H.G. & Cummings, C.M., 1939. 'Analysis of gas emboli'. U.S. Army Air Corps, Wright Field, Engng. Sect. Memo. Report, EXP-M-54-653-3.

Atkinson, J.R., 1963. 'Experimental air embolism'. NW. Med., Seattle, 62, 699-703.

Averyanov, V.A., 1964. 'Some conditions for the increase in body resistance to decompression disorders under the repeated effects of decompression'. In Brestkin, M.P. (Ed.), 34-39.

Averyanov, V.A. & Mikhailov, P.M., 1962. 'Cause and prevention of osteo-articular disorders in decompression sickness'. Gig. Truda prof. Zabol., 25-30, (NSTIC Translation, 1624).

Bailey, H., 1956. 'Air embolism'. J. Int. Coll. Surg., 25 675-688.

Baird, R.J., Miyagishima, R.T. & Labrosse, C.J., 1964. 'Vasodilating action of intra-arterial oxygen emboli'. Archs. Surg., Chicago, 88, 23-35.

Baker, R.D., 1945. 'The internal lesions in burns, with special reference to the liver and to the splenic nodules. An analysis of 96 autopsies'. Am. J. Path., 21, 717-739.

Balke, B. & Wells, J.G., 1958. 'Ceiling altitude tolerance following physical training and acclimatisation'. J. Aviat. Med., 29, 40-47.

Barcroft, J., Douglas, C.G., Kendal, L.P. & Margaria, R., 1931. 'Muscular exercise at low barometric pressure'. Archo. Sci. biol., 16, 609-615.

Barnard, E.E.P., Hanson, J.M., Rowton-Lee, M.A., Morgan, A.G., Polak, A. & Tidy, D.R., 1966. 'Post-decompression shock due to extravasation of plasma'. Br. Med. J., (ii), 154-155.

Barnard, P.J., 1957. 'Pulmonary arteriosclerosis due to oxygen, nitrogen and argon embolism'. Archs Path., 63, 322-332.

Bateman, J.B., 1951. 'Review of data on value of pre-oxygenation in prevention of decompression sickness'. Pt. I of Chapter 9 in Fulton, J.F. (Ed.).

Bauer, R.O., Campbell, M., Goodman, R., Munsat, T.L. & Pops, M.A., 1965. 'Aeroembolism treated by hypothermia'. Aerospace Med., 36, 671-675.

Béhague, P. & Garsaux, P., 1930. 'Paralysie transitoire après diminution de l'oxygène respiré aux très hautes altitudes (anoxhémie cerebrale vraisemblable)'. Revue neurol., 53, 77-79.

Behnke, A.R. Jr., 1932. 'Analysis of accidents occurring in training with the submarine lung'. Nav. Med. Bull., 30, 177-185.

Behnke, A.R. Jr., 1945. 'The absorption and elimination of gases in the body in relation to its fat and water content'. Medicine, Baltimore, 24, 359-380.

Behnke, A.R. Jr., Feen, B.G. & Welham, W.C., 1942. 'The specific gravity of healthy men, body weight + volume as an index of obesity'. J. Am. Med. Ass., 118, 495-498.

Bell, E.T., 1950. 'Renal Diseases'. 2nd Edition. London, Kimpton, pp. 448.

Belt, T.H., 1939. 'Liver necrosis following burns, simulating the lesions of yellow fever'. J. Path. Bact., 48, 493-498.

Benjamin, R.B., Turbak, G.E. & Lewis, F.J., 1957. 'The effects embolism in the systemic circulation and its prevention during open card surgery'. J. thorac. Surg., 34, 548-552.

Bennison, W.H., Catton, M.J. & Fryer, D.I., 1965. 'Fatal decompression sickness in a compressed-air worker'. J. Path. Bact., 89, 319-329.

Benzinger, T., 1950. 'Explosive decompression'. Chapter IVM, in 'German Aviation Medicine in World War II', Dept. of the Air Force, U.S. Govt. Printing Office, Washington D.C., Vol. 1, 404-408.

Bergeret, P.M., 1937. 'Effets physiologiques de l'altitude en avion'. Revue Serv. santé milit., 107, 325-353.

Berkinshaw-Smith, E.M.I., Morgan, R.S. & Payling-Wright, G., 1962. 'Permeability response of cerebral and cutaneous blood vessels to vasoactive agents'. Nature, Lond., 196, 173.

Berry, C.A., 1957. 'Decompression sickness as a problem in operations and training in the USAF'. Paper to Int. Congr. Aviat. Med. Stockh.

Berry, C.A., 1960. 'Dysbarism: an in-flight case and a discussion of the present status'. Paper to Europ. Congr. Aviat. Med., Lond., Later published in 'Human Problems of Supersonic and Hypersonic Flight', (1962), Ed. Barbour, A.B. & Whittingham, H.E., Oxford, Pergamon, 325-338.

Berry, C.A. & Hekhuis, G.L., 1960. 'X-ray survey for bone changes in low-pressure chamber operators'. Aerospace Med., 31, 760-765.

Berry, C.A. & Smith, M.R., 1962. 'Recent USAF experience with in-flight dysbarism'. Aerospace Med., 33, 995-1000.

Bert, P., 1878. 'La pression barométrique; recherches de physiologie expérimentale'. Paris, Masson. pp.1168. (Translation by Hitchcock, M.A. & Hitchcock, F.A., 'Barometric pressure; researches in experimental physiology'. Columbus, College Book Co., 1943).

Beyer, D.H., 1962. 'The SAM decompression sickness management team'. (Abstract) Aerospace Med., 33, 328-329.

Beyne, J., 1923. 'Sur l'origine des accidents provoqués chez l'homme par les fortes dépressions atmosphériques et sur la protection de l'aviateur contre les troubles d'ordre anoxhémique'. C.r. hebd. Séanc. Acad. Sci., Paris, 176, 1920-1923.

Bing, R.J., Castellanos, A., Gradel, E., Lupton, C. & Siegel, A., 1956. 'Experimental myocardial infarction: circulatory, biochemical and pathologic changes'. Am. J. Med. Sci., 232, 533-554.

Blinks, L.A., Twitty, V.C. & Whitaker, D.M., 1951. 'Bubble formation in frogs and rats'. Part II of Chapter 5 in Fulton, J.F. (Ed.).

Boerema, B., 1965. 'Appearance and regression of pulmonary arterial lesions after repeated intravenous injection of gas'. J. Path. Bact., 89, 741-744.

Bond, R.F., Durant, T. & Oppenheimer, M.J., 1965. 'Hemodynamic alterations produced by intra-arterial gas emboli'. Am. J. Physiol., 208, 984-992.

Boothby, W.M. & Lovelace, W.R. II, 1938. 'Oxygen in aviation. The necessity for the use of oxygen and a practical apparatus for its administration to both pilots and passengers'. J. Aviat. Med., 9, 172-198.

Borden, C.W. & Hall, W.H., 1951. 'Fatal transfusion reactions from massive bacterial contamination of blood'. New. Engl. J. Med., 245, 760-765.

Bourne, J.G., 1957. 'Fainting and cerebral damage. A danger in patients kept upright during dental gas anaesthesia and after surgical operations'. Lancet, (ii), 499-505.

Boycott, A.E. & Damant, G.C.C., 1908A. 'Experiments on the influence of fatness on susceptibility to caisson disease'. J. Hyg., Camb., 8, 445-456.

Boycott, A.E. & Damant, G.C.C., 1908B. 'Some lesions of the spinal cord produced by experimental caisson disease'. J. Path. Bact., 12, 507-515.

Boycott, A.E., Damant, G.C.C. & Haldane, J.S., 1908. 'The prevention of compressed air illness'. J. Hyg., Camb., 8, 342-442.

Boycott, A.E. & Haldane, J.S., 1908. 'The effects of low atmospheric pressure on respiration'. J. Physiol., Lond., 37, 355-377.

Boyer, N.H. & Curry, J.J., 1944. 'Bronchospasm associated with pulmonary embolism: respiratory failure'. Archs intern. Med., 73, 403-409.

Brånemark, P.I. & Lindström, J., 1964. 'Microcirculatory effects of emulsified fat infusions'. Circulation Res., 15, 124-130.

Bratt, H.R., 1961. 'Report on severe dysbarism treated with Navy recompression chamber'. Unpubl. report, USAF.

Brauer, L., 1933. 'Das Institut für Luftfahrtmedizin und Klimasforschung am Eppendorfer Krankhaus zu Hamburg'. Acta aerophysiol., 1, 5-13.

Brestkin, A.P., 1964. 'Relationship between the supersaturation coefficient of gas-liquid systems and the tension of dissolved gas'. in Brestkin, M.P. (Ed.), 10-17.

Brestkin, A.P., Gramenitskii, P.M. & Sidoro, N.Ya., 1964. 'Study of the safe supersaturation of the body with indifferent gases at different pressures'. in Brestkin, M.P. (Ed.), 18-27.

Brestkin, M.P., (Ed.), 1964. 'Funktsii organizma v usloviyakh izmenennoi gazovoi sredy' (The effect of the gas medium and pressure on body function) Acad. nauk. SSSR, inst. evolyutsionnoi fiziologii im I.M. Sechenov, Moskva. NASA Transl. TT F-358.

Brierley, J.B., 1963. 'Neuropathological findings in patients dying after open-heart surgery'. Thorax, 18, 291-304.

Brierley, J.B. & Excell, B.J., 1966. 'The effects of profound systemic hypotension upon the brain of M. Rhesus. Physiological and pathological observations'. Brain, 89, 269-298.

Brierley, J.B., & Miller, A.A., 1966. 'Fatal brain damage after dental anaesthesia. Its nature, aetiology, and prevention'. Lancet, (ii), 869-873.

Bromley, J. & Harvey, W., 1944. 'Radiology at simulated high altitudes'. Air Ministry, London, Flying Pers. Res. Comm., FPRC Report 626.

Brown, B.R., 1946. 'The incidence and relation of syncope to decompression sickness'. J. Aviat. Med., 17, 257-264.

Brown, E.W., 1931. 'Shock due to excessive distension of the lungs during training with escape apparatus'. Nav. Med. Bull., 29, 366-370.

Brown, G.A., Cronick, C.H., Motley, H.L., Kocour, E.T. & Klingman, W.O., 1945. 'Nervous system dysfunction in adaptation to high altitude and as postflight reactions'. War Med., Chicago, 7, 157-161.

Brown, H.H.S., 1966. 'The pressure cabin'. Chapter 9 in Gillies, J.A. (Ed.).

Brunner, F.P., Frick, P.G. & Bühlmann, A.A., 1964. 'Post-decompression shock due to extravasation of plasma'. Lancet, (i), 1071-1073.

Bywaters, E.G.L., 1946. 'Anatomical changes in the liver after trauma'. Clin. Sci., 6, 19-40.

Caldini, P., 1965. 'Pulmonary hemodynamics and arterial oxygen saturation in pulmonary embolism'. J. appl. Physiol., 20, 184-190.

Cameron, G.R., Burgess, F. & Trenwith, V., 1946. 'An experimental study of some effects of acute anhydraemia'. J. Path. Bact., 58, 213-220.

Cameron, G.R. & De, S.N., 1949. 'Experimental pulmonary oedema of nervous origin'. J. Path. Bact., 61, 375-387.

Cameron, G.R. & Karunaratne, W.A.E., 1936. 'Carbon tetrachloride cirrhosis in relation to liver regeneration'. J. Path. Bact., 42, 1-21.

Cammermeyer, J., 1953. 'Subacute cerebral fat embolism complicated by juxtaembolic thrombosis of fibrin'. Archs Path., 56, 254-261.

Cammermeyer, J. & Adams, R.D., 1954. 'An analysis of the mechanism and a study of the morbid anatomy of neurological disorders incident to operations on the neck and thorax'. Acta psychiat. neurol. scand., Suppl. 96, pp.61.

Cammermeyer, J. & Gjessing, R., 1951. 'Fatal myocardial fat embolism in periodic catatonia with fatty liver'. Acta med. scand., 139, 358-367.

Campbell, J.A. & Hill, L., 1933. 'Studies in saturation of the tissues with gaseous nitrogen, III Rate of saturation of goat's brain, liver and bone marrow in vivo with excess nitrogen during exposure to +3, +4 and +5 atmospheres pressure'. Q. Jl exp. Physiol., 23, 219-227.

Cannon, P. & Gould, T.R., 1964. 'Treatment of severe decompression sickness in aviators'. Br. Med. J., (1), 278-282.

Carey, T.M., 1958. 'A case of bends originating at the site of a polio vaccination given 6 days previously'. RCAF Aeromed. Rep., 65-67.

Catchpole, H.R. & Gersh, I. 1946. 'Physiological factors affecting the production of gas bubbles in rabbits decompressed to altitude'. J. cell. comp. Physiol., 27, 15-26.

Catchpole, H.R. & Gersh, I., 1947. 'Pathogenetic factors and pathological consequences of decompression sickness'. Physiol. Rev., 27, 360-397.

Catto, M.E. & Fryer, D.I., Jan. 1965. 'Bone changes in caisson disease'. Dem. to Path. Soc. Gt Br. Irel.

Cheetham, R.W.S., 1947. 'Incidence of decompression sickness in individuals tested in a decompression chamber situated at 4,700 feet'. J. Aviat. Med., 18, 279-288.

Chryssanthou, C., Kalberer, J., Kooperstein, S. & Antopol, W., 1964. 'Studies on dysbarism. II. Influence of bradykinin and ''bradykinin-antagonists'' on decompression sickness in mice'. Aerospace Med., 35, 741-746.

Clark, B. & Graybiel, A., 1957. 'The break-off phenomenon. A feeling of separation from the earth experienced by pilots at high altitudes'. J. Aviat. Med., 28, 121-126.

Clark, D.M., 1945. 'To report two cases of pneumomediastinum following explosive decompression'. USAAF Engng. T SEAL-3-695-29-I.

Clay, J.R., 1963. 'Histopathology of experimental decompression sickness'. Aerospace Med., 34, 1107-1110.

Coburn, K.R., 1956. 'Preliminary investigation of bone changes associated with decompression sickness'. (Abstract). J. Aviat, Med., 27, 163.

Coburn, K.R., 1962. 'Decompression sickness: present status'. J. R. nav. med. Serv., 48, 69-76.

Coburn, K.R., Gould, T.R., Young, J.M., Hatfield, M., Colley, I.H. & Boyd-Martin, E., 1962. 'Decompression collapse syndrome: Report of a case successfully treated by compression to a pressure in excess of one atmosphere'. Aerospace Med., 33, 1211-1215.

Cockett, A.T.K. & Nakamura, R.M., 1963. 'Dysbarism: a review with emphasis on recent findings'. Precirc. abst. 34th Aerospace Med. Ass. Ann. Meeting, Los Angeles.

Cockett, A.T.K. & Nakamura, R.M., 1964. 'A new concept in the treatment of decompression sickness (Dysbarism)'. (Letter). Lancet,(1), 1102.

Cockett, A.T.K. & Nakamura, R.M., 1965. 'A new approach to dysbarism: successful therapy without recompression'. Preprint, 36th Aerospace Med. Ass. Ann. Meeting, N.Y.

Cockett, A.T.K., Nakamura, R.M. & Franks, J.J., 1963A. 'Experimental dysbarism: delayed shock secondary to plasma deficit'. Precirc. abstr., 34th Aerospace Med. Ass. Ann. Meeting, Los Angeles.

Cockett, A.T.K., Nakamura, R.M. & Franks, J.J., 1963B. 'Delayed shock in experimental dysbarism'. Surg. Forum, 14, 7-8.

Cockett, A.T.K., Nakamura, R.M. & Kado, R.T., 1965. 'Physiological factors in decompression sickness'. Archs envir. Hlth, 11, 760-764.

Cohen, A.C., Glinsky, G.C., Martin, G.E. & Fetterhoff, K.L., 1951. 'Air embolism'. Ann. intern. Med., 35, 779-784.

Colebatch, H.J.H., 1964. 'Responses of the lung to pulmonary embolism'. Lect. Postgrad. Med. School, Hammersmith, 11 May, 1964.

Colebatch, H.J.H. & Dekock, M.A., 1963. 'Histamine release in embolism of the lung with barium sulphate'. Fedn Proc. Fedn Am. Socs exp. Biol., 22, 282.

Colebatch, H.J.H., Dekock, M.A., Nadel, J.A. & Olsen, C.R., 1964. 'Lung constriction in embolism with barium sulphate'. J. Physiol., Lond., 170, 1P.

Collins, J. J., 1962. 'An usual case of air embolism precipitated by decompression'. New Engl. J. Med., , 595-598.

Colonna, P.C. & Jones, E.D., 1948. 'Aeroembolism of bone marrow. An experimental study'. Archs Surg., Chicago, 56, 161-171.

Comroe, J.H. Jr, Forster, R.E., Dubois, A.B., Briscoe, W.A. & Carlsen, E., 1962. 'The lung. Clinical physiology and pulmonary function tests'. 2nd Edn., Chicago, Year Book Med. Publ. Inc. pp. 390.

Cook, S.F., 1951. 'Role of exercise, temperature, drugs and water balance in decompression sickness'. Part II of Chapter 8 in Fulton, J.F. (Ed.).

Corcoran, A.C. & Page, I.H., 1945. 'Post-traumatic renal injury. Summary of experimental observations'. Archs Surg., Chicago, 51, 93-101.

Corning, J.L., 1890. 'Observations on the caisson or tunnel disease, with notes on nine cases which occurred at the engineering works known as the Hudson Tunnel'. Med. Rec., N.Y., 37, 513-521.

Cotes, J.E., 1952. 'Notes on the incidence of cases of collapse in RAF decompression chambers'. Air Min., Lond., Flying Pers. Res. Comm., FPRC/Memo 33.

Cotes, J.E., 1953. 'Decompression sickness with post decompression collapse. An account of three cases'. Air Min., Lond., Flying Pers. Res. Comm., FPRC Report 825.

Cotes, J.E., 1965. 'Lung function. Assessment and application in medicine'. Oxford, Blackwell, pp. 540.

Cotes, J.E. & Gronow, D.G.C., 1952. 'Further analysis of cases of descent in decompression chamber tests of 610 flying personnel'. Air Min., Lond., Flying Pers. Res. Comm., FPRC Report 794.

Crouzon, O., 1911. 'La physiologie des aviateurs et des aéronautes'. 5th Cong. int. Aéronaut., Turin, 409-412.

Cruchet, R., 1921. 'Que-ce que le mal des aviateurs?' 1st Congr. int. Navig. aerienne, Paris, 4, 389-390.

Cruchet, R. & Moulinier, R., 1911. 'Le mal des aviateurs'. C. r. hebd. Séanc. Acad. Sci., Paris, 152, 1114-1115.

Cruchet, R. & Moulinier, R., 1920. 'Air sickness: its nature and treatment'. London, Bale, Sons & Danielsson, pp. 96.

Cunningham, D.J.C. & Lloyd, B.B. (Ed.). 'The regulation of human respiration'. Oxford, Blackwell, pp. 591.

Cuppage, F.E., 1963. 'Fat embolism in diabetes mellitus'. Am. J. clin. Path., 40, 270-275.

Cutler, K.R., 1962. 'Decompression sickness - a review of eleven hospitalized cases'. NATO AIRCENT 8th Ann. Med. Conf., 37-41.

Daly, I. de B. & Fegler, J., 1942. 'Gas bubbles in circulating blood of decompressed animals'. Air Min., Lond., Flying Pers. Res. Comm., FPRC Report 478.

Damato, M. J., Highly, F. M., Hendler, E., & Michel, E. L., 1963. 'Rapid decompression hazards after prolonged exposure to 50 per cent oxygen - 50 per cent nitrogen atmosphere.' Aerospace Med., 34, 1037-1040.

Damato, M. J., Kellett, G. L., & Coburn, K. R., 1965. 'The incidence of aeroembolism resulting from rapid decompression following exposure to a mixed gas atmosphere at a pressure of 380 mmHg.' US Navy Report, NAEC-ACEL-529.

Danis, R. K., & Willman, V. L., 1963. 'Cerebral air embolism effects on brain water and serotonin content'. Surg. Forum, 14, 63-65.

D'Aubigné, R. M., 1964. 'Idiopathic necrosis of the femoral head in adults'. Ann. R. Coll. Surg., 34, 143-160.

Davidson, J. K., 1964A. 'Pulmonary changes in decompression sickness. Some observations on compressed air workers at the Clyde Tunnel'. Clin. Radiol., 15, 106-111.

Davidson, J. K., 1964B. 'Radiology in decompression sickness: the Clyde Tunnel'. Scott. Med. J., 9, 1-9.

Davis, H. A., 1940. 'Acute circulatory failure (shock) following subcutaneous injection of hypertonic sodium chloride solution'. Proc. Soc. Exp. Biol. Med., 45, 354-356.

Davis, H. A., 1941. 'Pathology of dehydration shock'. Archs Surg., Chicago, 42, 939-955.

Davis, H. A., 1949. 'Shock and allied forms of failure of the circulation'. New York, Grune & Stratton, pp. 595.

Dension, D. M., Ledwith, F. & Poulton, E. C., 1966. 'Complex reaction times at simulated cabin altitudes of 5,000 feet and 8,000 feet'. Aerospace Med., 37, 1010-1013.

Denney, M. K., & Glas, W. W., 1964. 'Experimental studies in barotrauma'. J. Trauma, 4, 791-796.

Denney, M. K., & Read, R. C., 1965. 'Scuba-diving deaths in Michigan'. J. Am. Med. Ass., 192, 220-222.

Dept. of the Air Force., 1950. 'German Aviation Medicine in World War II'. 2 vol., Washington, Govt. Printing Office.

De Vries. E., 1962. - in discussion period, NATO AIRCENT 8th Ann. Med. conf., 60.

Dick, M., 1939. 'The respiratory and circulatory responses to intravenous oxygen and their relation to anoxemia'. Am. J. Physiol., 127, 228-231.

Döbeln, W. von & Höök, O., 1954. 'Olycksfall vid Undertryckskamnarprov'. Medd. Flyg. med., 4, 14-16.

Donald, K. W., 1955. 'Oxygen bends'. J. appl. Physiol., 7, 639-644.

Donnell, A.M. Jr. & Norton, C.P., 1960. 'The successful use of the recompression chamber in severe decompression sickness with neurocirculatory collapse'. Aerospace Med., 31, 1004-1009.

Dorfmann, H.D., Norman, A. & Wolff, H., 1966. 'Fibrosarcoma complicating bone infarction in a caisson worker. A case report'. J. Bone Jt Surg., 48A, 528-532.

Downey, V.M., Worleg, T.W. Jr, Hackworth, R. & Whitley, J.L., 1963. 'Studies on bubbles in human serum under increased and decreased atmospheric pressures'. Aerospace Med., 34, 116-118.

Duff, F., Greenfield, A.D.M. & Whelan, R.F., 1953. 'Vasodilatation produced by experimental arterial gas embolism in man'. Lancet, (ii), 230-234.

Duff, F., Greenfield, A.D.M. & Whelan, R.F., 1954. 'Observations on the mechanism of the vasodilatation following arterial gas embolism'. Clin. Sci., 13 365-376.

Duffner, G.J., 1962. 'Decompression sickness and its prevention among compressed air workers'. Seattle, Wash., Muncip. Metrop. Seattle, pp.35.

Dunn, J.S., 1920. 'The effect of multiple embolism of pulmonary arterioles'. Q. Jl. Med., 13, 129-147.

Durant, T.M., 1953. 'Acute obstruction of the pulmonary circulation'. Penn. Med. J., 56, 279-283.

Durant, T.M., Long, J.M. & Oppenheimer, M.J., 1947. 'Pulmonary (venous) air embolism'. Am. Heart J., 33, 269-281.

Durant, T.M., Oppenheimer, M.J., Webster, M.R. & Long, J., 1949. 'Arterial air embolism'. Am. Heart J., 38, 481-500.

Durlacher, S.H., Meier, J.R., Fisher, R.S. & Lovitt, W.V., 1954. 'Sudden death due to pulmonary fat embolism in persons with alcoholic fatty liver'. Am. J. Path., 30, 633-634.

Durlacher, S.H., Meier, J.R., Fisher, R.S. & Lovitt, W.V., 1958. 'Sudden death due to pulmonary fat embolism in chronic alcoholics with fatty liver'. Acta Med. leg. soc., 11, 229-230.

Dybowski, W., 1933. 'Die Depressionskammer des Zentrums für Flugärztliche Untersuchungen in Warschau'. Acta aerophysiol., 1, 83-86.

Ellenberg, M. & Osserman, K.E., 1951. 'The role of shock in the production of central liver cell necrosis'. Am. J. Med., 11, 170-178.

Elmino, O., 1965. 'Comportamento degli elementi figurati del sangue e de midollo nel barotrauma'. Folia Med., Napoli, 48, 783-787.

E.L.W., 1910. 'Effect of altitude in air and water', (Letter). Flight, 2(ii), 918.

Emery, E.R.J. 1962. 'Air embolism. A report of two cases, one treated successfully'. Anaesthesia, 17, 455-466.

End, E., 1963. In discussion of paper by Robb, H.J. Ann. Surg., 158, 695-696.

Engel, G.L., Webb, J.B., Ferris, E.B., Romano, J., Ryder, H. & Blankenhorn, M.A., 1944. 'A migraine-like syndrome complicating decompression sickness'. War Med., Chicago, 5, 304-314.

Erdman, S., 1907. 'Aeropathy or compressed air illness among tunnel workers'. J. Am. Med. Ass., 49, 1665-1670.

Ericsson, J.A., Gottlieb, J.D. & Sweet, R.B., 1964. 'Closed-chest cardiac massage in the treatment of venous air embolism'. New Engl. J. Med., 270, 1353-1354.

Ernsting, J., 1960. 'Some effects of oxygen breathing on man'. Proc. R. Soc. Med., 53, 96-98.

Ernsting, J., 1961. 'The effect of breathing concentrations of oxygen upon the diffusing capacity of the lung in man'. J. Physiol., Lond., 155, 51-52P.

Ernsting, J., 1965. 'Influence of alveolar nitrogen concentration and environmental pressure upon the rate of gas absorption from non-ventilated lung'. Aerospace Med., 36, 948-955.

Evelyn, K., 1941. 'The effects of low barometric pressure on the healthy adult male in the age group 19-32'. RCAF un-numbered report.

Fadell. E.J. & Sullivan, B.H., 1957. 'Fatty liver and fat embolism'. U.S. Arm. Forces Med., J., 8, 114-119.

Fahr, E., 1940. 'Experimentelle Untersuchungen über das Wesen der Caisson-krankheit'. Zentbl. allg. Path. path. Anat., 75, 257-261.

Farhi, K.E., Homma, T., Berger, D. & Busby, D., 1962. 'Tissue N_2 wash-out in the whole animal and in individual organs'. Physiologist, 5, 138.

Fati, S., Castellino, N. & Pallotta, R., 1964. 'Problemi de prevenzione e terapia dell'embolia gassosa traumatica'. Folia med., Napoli, 47, 1294-1305.

Fati, S. & Pallotta, R., 1961. 'Osservazione sulla terapia dei barotraumi'. Folia med., Napoli, 44, 1-12.

Fawcett, E. & Blachford, J.V., 1901. 'The frequency of an opening between the right and left auricles at the seat of the foetal foramen ovale'. J. Anat., 35, 67-70.

Fazekas, I.E., 1965. 'Alterations microscopiques dans des cas de mort par choc, d'origines différentes'. Ann. Med. leg., 45, 145-150.

Fellowes, P.F.M., Blacker, L.V.S., Etherton, P.T. & Douglas & Clydesdale, Marq. of, 1963. 'First over Everest. The Houston-Mount Everest Expedition, 1933'. London, John Lane, pp. 279.

Ferris, E.B. & Engel, G.L., 1951. 'The clinical nature of high altitude decompression sickness'. Chap. 2. in Fulton, J.F. (Ed.).

Fine, J., 1963. 'Air embolism', (Letter). Lancet, (i), 605.

Fischer, H., 1963. 'Beitrag zur Frage der Fettembolic bei Tödlicher Druckfall-krankheit'. Mschr. Unfallheilk. versich Med., 66, 318-322.

Fitzpatrick, F. L. & Stiles, K. A., 1944. 'The biology of flight'. London, Allen & Unwin, pp. 162.

Flack, M., 1919. ' "Flying Sickness". A discussion of its cause and the best means of combatting it'. Scient. Am. Suppl., 87, 262.

Fleck, P. D., 1961. 'Direct observations of the effects of arterial gas embolism'. B. Sc. thesis, Queen's Univ., Belfast.

Flinn, D. E. & Womack, G. J., 1963. 'Neurological manifestations of dysbarism - a review and report of a case with multiple episodes'. Aerospace Med., 34, 956-962.

Foley, A. E., 1863. 'Du travail dans l'air comprimé. Etude médicale, hygiénique et biologique faite au pont d'Argenteuil'. Paris - Quoted by Bert, P.

Fournier, A. M. & Jullien, G., 1965. 'La maladie ostéo-articulaire des caissons'. Paris, Masson. pp. 158.

Fraser, A. M., 1942. 'A study of the possible relation of susceptibility to de-compression sickness to the rate of blood denitrogenation and to corporeal specific gravity'. App. J. to Proc. 15th Meetg, Nat. Res. Coun. Exec. of Assoc. Comm. on Aviat. Med. Res., Ottawa, 29 July, 1942.

Fraser, A. M. & Rose, B., 1942. 'The effect of low temperature on decom-pression sickness'. Report from No. 1 Clin. Invest. Unit A31, RCAF.

Fraser, A. M. & Waters, E. T., 1942. 'The effect of hydrostatic pressure on the amelioration of symptoms of decompression sickness'. App. C to Proc. 15th Meetg, Nat. Res. Coun. Exec. of Assoc. Comm. on Aviat. Med. Res., Ottawa, 29 July, 1942.

Freeman, M. A. R., 1962. 'Heparin in the treatment of fat embolism'. Lancet, (i), 1302.

Fries, C. C., Levowitz, R., Adler, S., Cook, A. W., Karlson, K. E. & Dennis, C., 1957. 'Experimental cerebral gas embolism'. Ann. Surg., 145, 461-470.

Fryer, D. I., 1956. 'Fatal post-decompression shock'. Paper to Jt. Comm. Aviat. Path., Wash. D. C.

Fryer, D. I., 1957. 'Notes on the present state of knowledge concerning post-decompression shock'. Un-numbered report, RAF Inst. Aviat. Med., Farnborough.

Fryer, D. I., 1962A. 'Observations concerning the mechanism of subatmospheric decompression sickness'. NATO AIRCENT, 8th Ann. Med. Conf., 24-36.

Fryer, D. I., 1962B. 'Pathological findings in fatal subatmospheric decom-pression sickness'. Medicine Sci. Law, 2, 110-123.

Fryer, D.I., 1964. 'Decompression sickness at 18,500 feet. A case history with comment'. Aerospace Med., 35, 479-481.

Fryer, D.I., 1965A. 'Respiratory responses to gaseous embolism'. (Abstract). Aerospace Med., 36, 146.

Fryer, D.I., 1965B. 'A survey of an RAF decompression test at 28,000 feet'. AGARD Conf. Proc. CP2, 279-287.

Fryer, D.I., 1966. 'Preliminary physiological assessment of the RAE pressure/immersion suit (prototype form)'. RAF Inst. Aviat. Med. report 386, Farnborough.

Fryer, D.I. & Mason, J.K., 1955. Confidential Aviat. Path Report No. 1 Air Min., Lond.

Fryer, D.I. & Roxburgh, H.L., 1966. 'Decompression sickness', Chapter 10 in Gillies, J.A. (Ed.).

Fulton, J.F., 1948. 'Aviation medicine in its preventive aspects. An historical survey'. Oxford, University Press. pp. 174.

Fulton, J.F., (Ed.), 1951. 'Decompression sickness. Caisson sickness, diver's and flier's bends and related syndromes'. Philadelphia, Saunders. pp. 437. (Sponsored by the Division of Medical Sciences, National Academy of Sciences-National Research Council, Washington, D.C.)

Furry, D.E., 1964. 'Protection of vibrated rats exposed to explosive decompression'. Aerospace Med., 35, 773-775.

Furry, D.E., Reeves, E. & Beckman, E.L., 1966. 'Relationship of scuba-diving to the development of aviator's decompression sickness'. (Abstract). Aerospace Med., 37, 277.

Gable, W.D. & Townsend, F.M., 1962. 'Lung morphology of individuals exposed to prolonged intermittent supplemental oxygen'. Aerospace Med., 33, 1344-1348.

Garsaux, P., 1923. 'Le nouveau laboratoire à depression atmospherique et à basse temperature du Bourget'. Int. Air. Cong., Lond., Marsh, W.L. (Ed.) 709-727.

Garsaux, P., 1936. 'De quelques acquisitions en physiologie aérienne'. Aérophile, 44, 59-62.

Gatland, K., 1967. 'Manned Spacecraft. The pocket encyclopaedia of space-flight in colour'. London, Blandford. pp. 256.

Geraud, J., Rascol, A., Gleizes, L. & Moron, P., 1963. 'Embolie gazeuse cérébrale post-abortum'. Revue oto-neuro-ophth., 35, 65-67.

Gerbis, H. & Koenig, R., 1939. 'Drucklufterkrankungen (caissonkrankheiten)'. Arbeit. Gesundh., 35, pp. 196.

Gersh, I., 1945. 'Gas bubbles in bone and associated structures, lung and spleen of guinea-pigs decompressed rapidly from high-pressure atmospheres'. J. cell. comp. Physiol., 26, 101-117.

Gersh, I. & Catchpole, H.R., 1951. 'Decompression sickness: physical factors and pathologic consequences'. Chapter 7 in Fulton, J.F. (Ed.).

Gersh, I., Hawkinson, G.E. & Rathbun, E.N., 1944. 'Tissue and vascular bubbles after decompression from high pressure atmospheres - correlation of specific gravity with morphological changes'. J. cell. comp. Physiol., 24 35-70.

Gibson, W.C., 1962. 'Medical pioneers in aviation'. J. Hist. Med., 17, 83-93.

Gillies, J.A., (Ed.), 1966. 'A textbook of aviation physiology'. Oxford, Pergamon pp. 1226.

Gillman, J. & Gillman, T., 1948. 'Structure of the liver in fatal burns'. S. Afr. J. med. Sci., 13, 169-181.

Glaisher, J., Flammarion, C., De Fonville, W. & Tissandier, G., 1871. 'Travels in the air'. London, R. Bentley, pp. 398.

Glaister, D.H., 1965. 'Acceleration atelectasis - some factors modifying its occurrence and magnitude'. Min. Defence, Air Force Dep., Flying Pers. Res. Comm., FPRC/Memo 220.

Glas, W.W., Grekin, T.D. & Musselman, M.M., 1953. 'Fat embolism'. Am. J. Surg., 85, 363-369.

Gleason, D.F. & Aufderheide, A.C., 1953. 'Fatal bone marrow embolism occluding the pulmonary arteries'. Am. J. Med., 15, 137-140.

Goggio, A.F., 1943. 'Survey of chamber reactions observed and studied at 33rd Altitude Training Unit prior to Oct. 1st 1943 with related clinical studies'. U.S. Nat. Res. Coun., Comm. Aviat. Med., Un-numbered report, 20th Dec., 1943.

Goggio, A.F. & Houck, G.H., 1945. 'Physiologic abnormalities and pathologic changes following exposure to simulated high altitudes'. War Med., Chicago, 7, 152-156.

Golding, F.C., Griffiths, P., Hempleman, H.V., Paton, W.D.M. & Walder, D.N., 1960. 'Decompression sickness during construction of the Dartford Tunnel'. Br. J. ind. Med., 17, 167-180.

Goodman, M.W., 1964. 'Decompression sickness treated with compression to 2-6 atmospheres absolute'. Aerospace Med., 35, 1204-1212.

Gould, T.R., 1963. 'A review of the high-altitude Selection Test, 1961-1962'. J.R. nav. med. Serv., 49, 93-96.

Gowdey, C.W. & Philp, R.B., 1965. 'Etiology and treatment of experimental decompression sickness with special reference to body lipids'. Milit. Med., 130, 648-652.

Graham, R.L., 1944. 'Sudden death in young adults in association with fatty liver'. Bull. Johns Hopkins Hosp., 74, 16-25.

Gramenitskii, P.M. & Savich, A.A., 1964A. 'Provocation of caisson disease signs in animals emerging from increased pressure by subsequent ascent to altitude'. in Brestkin, M.P. (Ed.), 40-46.

Gramenitskii, P.M. & Savich, A.A., 1964B. 'Results of experimental analysis of decompression air embolism'. in Brestkin, M.P. (Ed.). 47-56.

Gray, J.S., 1951. 'Constitutional factors affecting susceptibility to decompression sickness'. Chapter 7 in Fulton, J.F. (Ed.).

Green, I.D. & Burgess, B.F., 1962. 'An investigation into the major factors contributing to post-flight chest pain in fighter pilots'. Min. of Defence, Air Force Dep., Flying Pers. Res. Comm., FPRC Report 1182.

Gribble, M. De G., 1954. 'Metabolic effects of high altitude decompression'. D.M. Thesis, Oxford.

Gribble, M. De G., 1960. 'A comparison of the high altitude and high pressure syndromes of decompression sickness'. Br. J. ind. Med., 17, 181-186.

Griffin, D.R., Robinson, S., Belding, H.S., Darling, R.C. & Turrell, E., 1943. 'The effects of cold and rate of ascent on aeroembolism'. U.S. Nat. Res., Coun., Com. Aviat. Med. Report 174.

Griffiths, P.D., 1959. 'Compressed air disease. A clinical review of cases and treatment'. M.D. Thesis, Cambridge.

Grodins, F.S., Ivy, A.C. & Adler, H.F., 1943. 'Intravenous administration of oxygen'. J. Lab. clin. Med., 28, 1009-1014.

Gross, P., 1934. 'The patency of the so-called "anatomically open but functionally closed" foramen ovale'. Am. Heart J., 10, 101-109.

Grow, M.C. & Armstrong, H.G., 1941. 'Fit to fly. A medical hand book for fliers'. New York, Appleton Century, pp.387.

Grulee, C.G., 1942. 'Eleven cases of "aeroembolism" requiring hospitalization'. U.S. Nat. Res. Coun., Comm. Aviat. Med., Report 172.

Guest, M.M., 1944. 'The incidence of bends during different periods of the day'. Air Surg. Bull, 1(6), 5.

Gupta, D.N., 1956. 'Acute changes in the liver after administration of thioacetamide'. J. Path. Bact., 72, 183-192.

Gusinskii, Z.S. & Shvarev, A.I., 1964. 'Severe spinal form of decompression sickness with a favourable outcome'. in Brestkin, M.P. (Ed.), 282-286.

Guyton, A.C., 1963. 'A concept of negative interstitial pressure based on pressures in implanted perforated capsules'. Circulation Res., 12, 399-414.

Halasz, N.A. & Marasco, J.P., 1957. 'An experimental study of fat embolism'. Surgery, St. Louis, 41, 921-929.

Halbouty, M.R. & Hessler, J.J., 1955. 'Severe neurocirculatory collapse at simulated altitude'. U.S. Arm. Forces Med. J., 6, 1363-1370.

Halbouty, M.R. & Long, D.R., 1953. 'Neurocirculatory collapse in aircraft flight. Report of a case'. J. Aviat. Med., 24. 301-307.

Haldane, J.S., 1922. 'Respiration'. New Haven & London, Yale Univ. Press & Oxford Univ. Press, pp. 427.

Haldane, J.S., 1935. Discussion of paper by Japp, H. Struct. Engr., 14, 305-310.

Haldane, J.S., Hamilton, F.T., Bacon, R.H.S. & Lees, E., 1907. 'Report of a Committee appointed by the Lords Commissioners of the Admiralty to consider and report upon the condition of deep water diving'. H.M.S.O. CN 1549/1907.

Hall, A.L., 1955A. 'Some effects of explosive decompression on albino rats: preliminary studies'. U.S. Navy School Aviat. Med., Res. Proj. NM 001-101-105-01.

Hall, A.L., 1955B. 'Some effects or rapid decompression to 43,000 feet on human subjects' incidence and severity of aerobullosis (aeroembolism) in a subject repeatedly exposed to terminal altitudes between 35,000 and 43.000 feet'. U.S. Navy, School Aviat. Med., Res. Proj. NM 001-101-103 Report No. 1.

Hall, W.H. & Gold, D., 1955. 'Shock associated with bacteremia'. Archs intern. Med., 96, 403-412.

Halmagyi, D.F.J., Starzecki, B. & Horner, G.J., 1964. 'Humoral transmission of cardiorespiratory changes in experimental lung embolism'. Circulation Res., 14 546-554.

Hamilton, V.H., 1964. 'Coma due to fat-embolism treated with hypothermia and dehydration'. Lancet,(ii), 994-995.

Hamlin, R.L., Marsland, W.P. & Smith, C.R., 1962. 'Absence of arteriovenous anastamoses in anaesthetised sheep'. Am. J. Physiol., 202, 961-962.

Hardie, C.D., Cullen, F.R. & Bryan, A.C., 1961. 'The role of fat embolism in the neurological manifestations of decompression sickness'. Paper to 4th Sci. Sess., Jt Comm. Aviat. Path., Downsview.

Harman, J.W. & Ragaz, F.J., 1950. 'The pathogenesis of experimental fat embolism'. Am. J. Path., 26, 551-564.

Harnett, R.W.F., Paterson, J.R.S., Lowe, K.G., Stewart, I.M. & Uytman, J.D., 1959. 'Treatment of cerebral fat embolism'. Lancet,(ii), 762-764.

Harrison, M.H.M., 1962. 'Cerebral fat embolism with haematemesis - report of a case'. J. Bone Jt. Surg., 44B, 794.

Hartman, F.W. & Romence, H.L., 1943. 'Liver necrosis in burns'. Ann. Surg., 118, 402-416.

Hartmann, H., 1961. 'Druckfallkrankheit und Intravasale Gasblasen'. Int. Z. angew. Physiol., 19, 67-79.

Hartmann, H. & Wünsche, O., 1961. 'Decompression sickness and air embolism'. Revue Méd. Aéronaut., 1, 152-153.

Hartroft, W.S., 1949. 'Histological studies on fatty infiltrations of the liver in choline-deficient rats'. in Sherlock, S. & Wostenholme, G.E.W. (Ed.), 90-96.

Hartroft, W.S., 1950. 'Accumulation of fat in liver cells and in lipodiastaemata preceding experimental dietary cirrhosis'. Anat. Rec., 106, 61-87.

Hartroft, W.S., 1953. 'Diagnostic significance of fatty cysts in cirrhosis'. Archs Path., 55, 63-69.

Hartroft, W.S., 1954. 'The sequence of pathological events in the development of experimental fatty liver and cirrhosis'. Ann. N.Y. Acad., Sci., 57 Art. 6, 633-645.

Hartroft, W.S., 1955. 'Fat emboli in glomerular capillaries of choline-deficient rats and of patients with diabetic glomerulosclerosis'. Am. J. Path., 31, 381-397.

Hartroft, W.S., 1963. 'The nature of fatty liver'. Lecture, Path. Dep., R. Free Hosp., London, 1 July, 1963.

Hartroft, W.S. & Ridout, J.H., 1951. 'Pathogenesis of the cirrhosis produced by choline deficiency. Escape of lipid from fatty hepatic cysts into the biliary and vascular systems'. Am. J. Path., 27, 951-989.

Hartroft, W.S. & Sellers, E.A., 1952. 'The dissolution of fatty cysts in pre-cirrhotic and cirrhotic livers of choline-deficient rats treated with lipotropic factors'. Am. J. Path., 28, 387-399.

Harvey, E.N., 1944. 'Decompression sickness and bubble formation in blood and tissues'. Harvey Lect. 40, 41-76.

Harvey, E.N., 1951. 'Physical factors in bubble formation'. Chapter 4 in Fulton, J.F. (Ed.).

Harveyson, K.B., Hirschfeld, B.E.E. & Tonge, J.K., 1956. 'Fatal air embolism resulting from the use of a compressed air diving unit'. Med. J. Aust., (1), 658-660.

Haymaker, W.E., 1957. 'Decompression sickness' in Lubarsch, O., Henke, F. & Rössle, R. (Ed.) Handb. spez. path. Anat. Histol. 13, (1), 1600-1663.

Haymaker, W.E. & Davison, C., 1950. 'Fatalities resulting from exposure to simulated high altitudes in decompression chambers'. J. Neuropath. exp. Neurol., 9, 29-59.

Haymaker, W.E. & Johnston, A.D., 1955. 'Pathology of decompression sickness - a comparison of the lesions in airmen with those in caisson workers and divers'. Milit. Med., 117, 285-306.

Haymaker, W.E., Johnston, A.D. & Downey, V.M., 1956. 'Fatal decompression sickness during jet aircraft flight. A clinico-pathologic study of two cases'. J. Aviat. Med., 27, 2-17.

Heard, G., 1936. 'Exploring the Stratosphere'. London, Nelson. pp.98.

Heim, J.W., 1937-38. 'Physiologic considerations governing high altitude flight'. J. aeronaut. Sci., 5, 189-192.

Heller, R., Marger, W., Schrotter, H. von. 1900. 'Luftdruckerkrankungen mit Besonderer Berücksichtigung der Sogenannten Caissonkrankheit'. Wien, Hölder, pp. 1230.

Henderson, Y., 1917. 'Effects of altitude on aviators'. Aviation, 2, 145-147.

Henderson, Y., 1919. 'The physiology of the aviator'. Science, N.Y., 49, 431-441.

Hendrix, R.C. & Fox, J.E., 1964. 'Relation of obesity and abnormalities of lipid metabolism to lipid embolization of lungs'. Am. J. clin. Path., 41, 55-60.

Henn, R.H.E., 1962. 'Gehirnbefunde nach Tod in der Unterdruckkammer'. Mschr. Unfallheilk. VersichMed., 65, 437-445.

Henn, R.H.E. & Wünsche, O., 1962. 'Experimental study of fat embolism in decompression'. Paper to 5th Int. Congr. Aviat. Space Med., Madrid.

Henry, F.M. & Ivy, A.C., 1951. 'Preselection tests'. Chapter 10 in Fulton, J.F. (Ed.).

Hermann, M.R., 1948. 'Les embolies graisseuses de la grande circulation'. Ann. Med. leg. soc., 28, 124-127.

Hill, L.E., 1912. 'Caisson sickness and the physiology of work in compressed air'. London, Arnold, pp. 255.

Hill, L.E., 1932. 'Altitudes to be reached by air pilots by breathing oxygen'. Nature, Lond., 130, 397.

Hill, L.E., 1933. 'Altitudes to be reached when breathing oxygen'. Q. Jl. exp. Physiol., 23, 45-47.

Hill, L.E., 1934. 'The limit of high flying when breathing oxygen'. Proc. R. Soc. B. 115, 298-306.

Hill, L.E., 1935. Discussion on paper by Japp, H. Struct. Engr., 14, 306-308.

Hill, L.E. & Greenwood, M., 1909. 'On the formation of bubbles in the vessels of animals submitted to a partial vacuum'. J. Physiol., Lond., 39, xxiii.

Hill, R.B., 1961. 'Fatal fat embolism from steroid-induced fatty liver'. New. Engl. J. Med., 265, 318-320.

Hills, B.A., 1966. 'A thermodynamic and kinetic approach to decompression sickness'. Occas. papers in physiol. No. 1, Adelaide, Lib. Bd. S. Aust., pp. 372.

Hodgson, C.J., Davis, J.C., Randolph, C.L. Jr & Chambers, G.H., 1968. 'Seven-year follow-up X-ray survey for bone changes in low pressure chamber operators'. Aerospace Med., 39, 417-421.

Holmstrom, F.M.G., 1958. 'Collapse during rapid decompression. Report of three cases'. J. Aviat. Med., 29, 91-96.

Holmstrom, F.M.G. & Beyer, D.H., 1965. 'Decompression sickness and its medical management. A team approach to the study of aviator's neurocirculatory collapse'. USAF School Aerospace Med., Proc. Decomp. Sickn. Mangmt. Team.

Höök, O., 1958. 'Dysbarism manifested by anterior spinal artery syndrome'. J. Aviat. Med., 29, 540-543.

Hornberger, W. & Benzinger, T., 1942. 'Druckfallkrankheit'. Luftfahrt-medizin, 7, 9-34.

Howard, P., Glaister, D.H. & Stewart, W.K., 1965. 'Effects of gaseous embolism on the pulmonary circulation'. (Abstract). Aerospace Med., 36, 149.

Houston, C.S., 1947. 'Occurrence of bends, scotomata and hemianopsia at altitudes below 20,000 feet'. J. Aviat. Med., 18, 165-168.

Hufner, R.F. & McNicol, C.A., 1958. 'The pathological physiology of microscopic pulmonary vascular shunts'. Archs Path., 65, 554-560.

Hugh, A.E. & Fox, J.A., 1963. 'Circulatory Cavitation. 'Bubbles in the blood'. Lancet, (ii), 717-718.

Hunter, A.R., 1962. 'Air embolism in the sitting position'. Anaesthesia, 17, 467-472.

Hyland, J.W., Smith, G.T., McGuire, L.B., Harrison, D.C., Haynes, F.W. & Dexter, L., 1963. 'Effect of selective embolization of various sized pulmonary arteries in dogs'. Am. J. Path., 204, 619-625.

Illingworth, R.D., 1967. '*In vitro* variation of viscosity of body fat during cooling'. Lancet, (i), 655-657.

Imre, Gy, 1962. 'Dekompressionsretinopathie'. Klin. Mbl. Augenheilk., 141, 12-23.

Inman, V.T. & Saunders, J.B. de C.M., 1944. 'Referred pain from skeletal structures'. J. nerv. ment. Dis., 99, 660-667.

Jackson, J.M., Pinkerton, P.H. & Wilson, L.R., 1962. 'Infarction of femoral marrow in a case of aplastic anaemia'. J. Path. Bact., 83, 562-564.

Jacobi, M., Klein, B., Rascoff, H., Kogut, B., Auerbach, R.W. & Jennings, J.E., 1946. 'Effect of intravenous administration of oxygen on shock in dogs and in human beings'. Archs. Surg., Chicago, 52, 42-49.

Jacques, C.N., 1925. 'Report on low temperature and low pressure chamber and plant at Le Bourget'. R. Aircraft. Estab. Report H. 1001.

James, C.C.M., 1945. 'Late bone lesions in caisson disease'. Lancet, (ii), 6-8.

Jaminet, A., 1871. 'Physical effects of compressed air and of the causes of pathological symptoms produced on man, by increased atmospheric pressure employed for the sinking of piers in the construction of the Illinois and St. Louis bridge over the Mississippi River at St. Louis, Missouri'. St. Louis, Ennis., pp. 135.

Japp, H., 1935. 'The prevention of compressed air illness'. Struct. Engr., 14, 173-186.

Jaques, W. E. & Saini, N., 1962. 'A physiologic and anatomic study of experimental fat embolism in dogs'. Expl. molec. Path., 1, 57-64.

Jones, H. B., 1951. 'Gas exchanged and blood-tissue perfusion factors in various body tissues'. Chapter 9 in Fulton, J. F. (Ed.).

Jongbloed, J., 1930. 'The composition of the alveolar air in man at altitudes up to 14,000 m.; partly without oxygen supply. The mechanical effect of very low atmospheric pressure'. 5th Congr. int. Navig. aerienne, Hague, 2, 1418-1450.

Jullien, G., Leandri, M. & Blein, L., 1954. 'L'accident grave de decompression. Etude expérimentale physiopathologique et pathogenic'. Proc. 11th int. Congr. occup. Med. leg. Med., Napoli, 3, 552-553.

Junod, V. T., 1834. 'Recherches physiologiques et thérapeutiques sur les effets de la compression et de la raréfaction de l'air, tant sur le corps que sur les membres isolés'. Paris, Libraire de Devill-Cavellin., pp. 23.

Kahlstrom, S. C., Burton, C. C. & Phemister, D. B., 1939. 'Aseptic necrosis of bone. I Infarction of bone in caisson disease resulting in encapsulated and calcified areas in diaphyses and arthritis deformans'. Surgery Gynec. Obstet., 68, 129-146.

Kalser, M. H., Ivy, H. K., Pevsner, L., Marbarger, J. P. & Ivy, A. C., 1951. 'Changes in bone marrow pressure during exposure to simulated altitude'. J. Aviat. Med., 22, 286-294 + 311.

Karpovich, P. V., 1944. 'Relation between bends and physical fitness'. Air Surg. Bull., 1(vi), 5.

Kent, S. P., 1954. 'Fat emboli in diabetes mellitus'. Am. J. Path., 30, 634.

Kershman, J. & Haddad, F., 1952. 'Cerebral fat embolism - an unusual case with recovery'. Can. med. Ass. J., 66, 95-97.

Kidd, D. J., 1966. 'Decompression sickness. Current trends in prophylaxis and treatment'. Med. Servs. J. Can., 22, 79-86.

Kiessling, R. J. & Duffner, G. J., 1960. 'The development of a test to determine the adequacy of decompression following a dive'. U.S. Navy, Exp. div. unit, Res. Rep. 2-60.

Kimble, S. T., 1961. 'Fatal non-traumatic fat embolism in an alcoholic'. Med. Ann. Distr. Columbia, 30, 283-287.

Kindwall, E. P., 1962. 'Metabolic rate and animal size correlated with decompression sickness'. Am. J. Physiol., 203, 385-388.

Kindwall, E. P., Boréus, L. O. & Westerholm, B., 1962. 'Failure to show change in rat tissue histamine and serotonin after rapid decompression'. Am. J. Physiol., 203, 389-390.

Kinsell, L.W. & Kahn, J.P., 1955. 'The use of corticoids in association with antibiotics in the management of unusually severe infections'. Ann. N.Y. Acad. Sci., 61 (Art. 2), 397-407.

Kinsey, J.L., 1954. 'Air embolism as a result of submarine escape training'. U.S. arm. Forces med. J., 5, 243-255.

Kirk, R. & Henry, A.J., 1944. 'Observations on the toxicity of stilbamidine'. Ann. trop. Med. Parasit., 38, 99-118.

Kleinfeld, M. & Wilson, J.T., 1956. 'Decompression sickness (compressed air illness) in a tunnelling operation'. A.M.A. Archs. ind. Hlth., 14, 539-542.

Knisely, M.H., 1943. 'Aeroembolism'. USAAF, MC Engng. Div. Aeromed. Lab. Rep., ENG-M-49-696-Ic.

Knisely, W.H., Wallace, J.M., Mahaley, M.S. & Satterwhite, W.M. Jr., 1957. 'Evidence including in vivo observations, indicating mechanical blockage rather than reflex vasospasm as the cause of gas in pulmonary embolization'. Am. Heart J., 54, 483-497.

Kruse, C.A., 1963. 'Air embolism and other skin diving problems'. NW Med., Seattle, 62, 525-529.

Kylstra, J.A., 1963. 'Air Embolism', (Letter). Lancet, (i), 720.

Łaba, L., 1963. 'Późne następstwa choroby kesonowej u nurków'. (Late consequences of decompression sickness in divers). Bull. Inst. mar. Med., Gdansk, 14, 209-214.

Laborit, H., Barthélémy, L. & Perrimond-Trouchet, R., 1961. 'Action de l'héparine dans le traitement des accidents de décompression'. Agressologie, 2, 229-235.

Lalli, G. & Paolucci, G., 1958. 'Comportement des transaminases pyruvique et glutamique-oxalacetque en fonction des troubles anatomo-pathologiques dans le serum du lapin sumis à décompression explosive'. Proc. 3rd Congr. Europ. Med. aéronaut., Louvain, 332-342.

Lansing, A.I., 1944. 'Treatment of aeroembolism'. Air Surg. Bull., 1(v), 5.

Larn, R.J., 1965. 'Report on the death of Michael Lancaster'. Nepton No. 12 (News Bull. Nav. Air Comd. Sub Aqua Club).

Lecomte, J., 1956. 'Endogenous histamine liberation in man'. in Wolstenholme G.E.W. (Ed.).

Leeuwe, H., 1961-62. 'Des bulles de gaz dans le sang après décompression rapide'. Aeromed. Acta., 8, 83-89.

Lemessurier, D.H. & Baxter, R., 1964. 'Evidence of decompression sickness during flights at 20,000 to 24,000 feet above base'. Med. J. Aust., (1), 188-191.

Lemessurier, D.H. & Hills, B.A., 1965. 'Decompression sickness - a thermodynamic approach arising from a study of Torres Strait diving techniques'. Hvalråd. Skr., 48, 54-84.

Lemessurier, D.H. & Hills, B.A., 1966. 'Gas unsaturation inherent in living tissue'. Paper to int. meeting Aerospace Med., Sydney.

Leverett, S. Jr, Bitter, H. L. & McIver, R. G., 1963. 'Studies in decompression sickness: circulatory and respiratory changes associated with decompression sickness in anaesthetised dogs'. USAF, School Aerospace Med., TDR-63-7.

Levy, E., 1922. 'Compressed-air illness and its engineering importance, with a report of cases at the East River Tunnels'. Tech. Pap. Bur. Mines, Wash., 285, pp. 47.

Liebow, A. A., Stark, J. E., Vogel, J. & Schaefer, K. E., 1959. 'Intrapulmonary air trapping in submarine escape training casualties'. U. S. Arm. Forces Med. J., 10, 265-289.

Lindenberg, R., 1956. 'Morphotropic and morphostatic necrobiosis - investigations on nerve cells of the brain'. Am. J. Path., 32, 1147-1177.

Lindsay, S. & Moon, H. D., 1946. 'Bone marrow embolism following fracture'. J. Bone Jt Surg., 28, 377-381.

Liske, E., Crowley, W. J. Jr. & Lewis, J. A., 1967. 'Altitude decompression sickness with focal neurological manifestations'. Aerospace Med., 38, 304-306.

Lourie, E. M., 1942. "Treatment of sleeping sickness in Sierra Leone'. Ann. trop. Med. Parasit., 36, 113-131.

Lovelace, W. R. II & Gagge, A. P., 1946. 'Aeromedical aspects of cabin pressurization for military and commercial aircraft'. J. aeronaut. Sci., 13, 143-150.

Lowenfels, A. B., Barbieri, R., Hartman, R. & Lord, J. W., 1963. 'Experimental arterial fat embolism'. J. Trauma, 3, 399-406.

Lucké, B., 1946. 'Lower nephron nephrosis. The renal lesions of the crush syndrome, of burns, transfusions and other conditions affecting the lower segments of the nephron'. Milit. Surg., 99, 371-396.

Luft, U. C., 1954. 'Explosive decompression'. in Handb. Resp. Physiol., USAF School Aviat. Med., San Antonio, 134-135.

Lundgren, C. E. G., 1965. 'Alternobaric vertigo - a diving hazard'. Br. Med. J. (ii), 511-513.

Lundgren, C. E. G. & Malm, L. U., 1966. 'Alternobaric vertigo among pilots'. Aerospace Med., 37, 178-180.

Lundin, G., 1953. 'Nitrogen elimination during oxygen breathing'. Acta. physiol. scand., 30, Suppl. 111, 130-143.

Lundin, G., 1960. 'Nitrogen elimination from the tissues during oxygen breathing and its relationship to fat: muscle ratio and the localization of bends'. J. Physiol., Lond., 152, 167-175.

Lutz, W., 1953. 'Experimentelle Untersuchungen zur Behandlung der Luftembolie mit Erhöhten Atmosphärendruck'. Anaesthesist., 2, 199-201.

Lyle, C.B. & Fitzgerald, J.B., 1961. 'Alteration of response of dogs to cerebral aeroemboli by pretreatment with procaine hydrochloride'. USAF, School Aerospace Med. Report 62-5.

Lynch, M.J.G., Raphael, S.S. & Dixon, T.P., 1959. 'Fat embolism in chronic alcoholism'. Archs Path., 67, 68-80.

McCallum, R.I., Walder, D.N., Barnes, R., Catto, M.E., Davidson, J.K., Fryer, D.I., Golding, F.C. & Faton, W.D.M., 1966. 'Bone lesions in compressed air workers, with special reference to men who worked on the Clyde Tunnels, 1958 to 1963'. J. Bone Jt Surg., 48B, 207-235.

MacClatchie, L.K., 'Medical aspects of submarine "lung" training'. Nav. med. Bull., 29, 357-366.

McIver, R.G. & Leverett, S.D. Jr., 1963. 'Studies in decompression sickness; cardiorespiratory responses of anesthetized dogs to compression therapy following experimental decompression sickness'. USAF, School Aerospace Med., TDR-63-94.

McLenechan, J., 1960. 'Diagnosis of fat embolism'. (Letter). Lancet (ii), 986-987.

McMurry, L., 1963. 'Wiley Post's aerospace achievements'. Paper for Oklahoma City Chamber of Commerce, 26th Sep. 1963.

McNutt, D.C., 1964. 'The overweight aviator and decompression sickness'. J.R. nav. med. Serv., 50, 4-6.

Mahady, C.F., 1943. 'A study of the blood and cardiovascular system following exposure to a simulated altitude of 38,000 feet'. US Nat. Res. Counc. Comm. Aviat. Med., Report 231.

Majumdar, K.K., 1957. 'Post decompression shock'. Aero med. Soc. J., India, 4, 9-14.

Malamud, N., Haymaker, W.E. & Custer, R.P., 1946. 'Heat Stroke. A clinico-pathologic study of 125 fatal cases'. Milit. Surg., 99, 397-449.

Malette, W.G., Fitzgerald, J.B. & Cockett, A.T.K., 1961. 'Dysbarism. A review of 35 cases with suggestions for therapy'. USAF, School Aerospace Med., Review 3-61.

Malette, W.G., Fitzgerald, J.B. & Eisman, B., 1960. 'Aero-embolus: a protective substance'. Surg. Forum, 11, 155-156.

Malhotra, M.S. & Wright, H.C., 1961A. 'Arterial air embolism during decompression and its prevention'. Proc. R. Soc. B., 154, 418-427.

Malhotra, M.S. & Wright, H.C., 1961B. 'The effects of a raised intrapulmonary pressure on the lungs of fresh unchilled cadavers'. J. Path. Bact., 82, 198-202.

Mallory, T.B., 1949. 'Systemic pathology consequent to traumatic shock'. J. Mt Sinai Hosp., 16, 137-148.

Malmejac, J., 1948. 'Médecine de l'aviation: bases physiologiques et physio-pathologiques'. Paris, Masson, pp.333.

Malmejac, J., Chardon, G. & Cruck, S., 1944. 'Sur la production d'embolies gazeuses dans les territoires cutanés sous les fortes dépressions barométriques'. C. r. hebd. Séanc. Acad. Sci., Paris, 138, 956-957.

Mandelbaum, L. & King, H., 1963. 'Pulmonary air embolism'. Surg. Forum, 14, 236-238.

Marbarger, J.P., Kadetz, W., Paltarokas, J., Variakojis, D., Hansen, J. & Dickinson, J., 1956. 'Gaseous nitrogen elimination at ground level and simulated altitude and the occurrence of decompression sickness'. USAF, School Aviat. Med., Report 55-73.

Marbarger, J.P., Kemp, W.E., Kadetz, W., Variakojis, D. & Hansen, J., 1957. 'Studies in aeroembolism'. USAF, School Aviat, Med., Report 57-44.

Marchand, P., Hasselt, H. van & Luntz, C.H., 1964. 'Massive venous air embolism'. S. Afr. med. J., 38, 202-208.

Marchoux, E. & Nepper., 1919. 'Influence de l'intégrité de la muqueuse rhino-pharyngienne sur l'aptitude des aviateur au vol'. C. r. Séanc. Soc. Biol, 82, 668-672.

Margaria, R., 1939. 'La possibilità di embolismo negli aviatori'. (Abstract). Luftfahrtmedizin, 3, 156.

Markham, T.N., 1967. 'Aseptic necrosis in a high altitude flier'. J. occup. Med., , 123-129.

Marotta, S.F., Marbarger, J.P., Andersen, N., Hansen, J. & Kadetz, W., 1961. 'Incidence of bends following partial denitrogenation at simulated altitude'. Aerospace Med., 32, 289-295.

Marshall, G.S., 1934. Letter quoted by Sir Henry Japp, in Japp, H., 1935.

Marshall, G.S., 1935. Discussion of Paper by Japp, H. Struct. Engnr. 14, 308.

Marshall, G.S., 1936. 'Medical notes on altitude flying'. Br. med. J. (ii), 731-732.

Marshall, G.S., 1937. 'Respiration in high flying'. Proc. R. Soc. Med., 30, 995-1006.

Masland, R.L., 1943A. 'Review of cases of collapse occuring in altitude chambers'. U.S. Nat. Res. Coun., Comm. Aviat. Med., Report 179.

Masland, R.L., 1943B. 'Recommendations for handling of reactions following altitude chamber flights'. USAAF, School Aviat. Med. Project 217, Report 1.

Masland, R.L., 1944. 'Collapse at high altitude'. Air Surg. Bull., 1(xi), 3-5.

Masland, R.L., 1946. 'Injury of the central nervous system resulting from decompression to simulated high altitude'. USAAF, School Aviat. Med., Project 481, Report 1.

Masland, R.L., 1948. 'Injury to the C.N.S. resulting from decompression to simulated high altitudes'. Archs Neurol. Psychiat., Chicago, 59, 445-456.

Mason, J.K., 1956. Confidential Aviat. Path. report to Air Ministry.

Mason, J.K., 1962. 'Aviation accident pathology - a study of fatalities'. London, Butterworth, pp. 358.

Matthews, B.H.C., 1939. 'Interim report on research on oxygen problems'. Air Ministry, Lond., Flying Pers. Res. Comm., FPRC Reports 60 and 70.

Mazella, G. & Paolucci, G., 1961. 'Istologia dell 'osse e variazioni ematiche dopo decompressione esplosiva'. Proc. 2nd World Congr. Aviat. Space Med., Rome, 506-518.

Meader, W.L., 1967. 'Decompression sickness in high-altitude flight'. Aerospace Med., 38, 301-303.

Mebane, J.C., 1955. 'Clinical neuropsychiatry in aviation medicine. A survey of one hundred military problem cases'. J. Aviat. Med., 26, 471-478.

Meijne, N.G., Schoemaker, G. & Bulterijs, A.B., 1963. 'The treatment of cerebral gas embolism in a high pressure chamber. An experimental study'. J. cardiovasc. Surg., 4, 757-763.

Miller, J.W., 1944. 'Pathologic changes in sheep resulting from exposure to low barometric pressures'. Publ. Hlth. Rep., Wash. 59, 618-620.

Ministry of Labour and National Service, 1958. 'Work in compressed air special regulations'. S.I. No. 61, London, H.M.S.O.

Mitscherlich, A. & Mielke, F., 1949. 'Doctors of infamy'. New York, Schuman, pp. 172.

Montanari, C. & Giaroli, M., 1962. 'Intorno alla identificazione de fattore umorale dell'embolia gassosa sperimentale con la enteramina'. Archo. Sci. biol., Bologna, 46, 11-23.

Moon, V.H., 1948. 'The pathology of secondary shock'. Am. J. Path., 24, 235-274.

Morant, G.M., 1946. 'Age-height-weight standards suitable for use in medical examinations of aircrew candidates'. Air Ministry, Lond., Flying Pers. Res. Comm., FPRC Report 653.

Morant, G.M., 1952. 'Results of tests in a decompression chamber of 610 flying personnel'. Air Ministry, Lond., Flying Pers. Res. Comm., FPRC Report 793.

Morgan, T.E., Ulvedal, F., Cutler, F.G. & Welch, B.E., 1963. 'Effects on man of prolonged exposure to oxygen at a total pressure of 190 mmHg'. USAF, School Aerospace Med., Report SAM-TDR-63-52.

Morse, W.I. & Soeldner, J.S., 1965. 'The measurement of human adipose tissue mass'. Chapter 65 in Renold, A.E. & Cahill, G.F. Jr. (Ed.).

Motley, H.L., Chinn, H.I. & Odell, F.A., 1945. 'Studies on bends', J. Aviat. Med. 16, 210-234.

Muir, R., 1941. 'Textbook of Pathology'. 5th Ed. London, Arnold, pp. 991.

Musgrave, S.M., 1935. 'Some notes on low-pressure research stations and their application to aeronautics'. Note to Air Ministry, London, dated 15th Jan. 1935.

Nadel, J.A., Colebatch, H.J.H. & Olsen, C.R., 1964. 'Location and mechanism of airway constriction after barium sulfate microembolism'. J. appl. Physiol., 19, 387-394.

Nasa, 1964. 'Bioastronautics data book'. Webb. P. (Ed.), Washington, NASA SP. 3006 pp. 400.

Naville, F. & Fromberg, C., 1913. 'Les embolies graisseuses. L'embolie graisseuse du cerveau'. Archs Méd., exp. Anat. path. 25, 405-429.

Nicholson, M.J. & Crehan, J.P., 1956. 'Emergency treatment of air embolism'. Anesth. Analg. curr. Res., 35, 634-643.

Niden, A.H. & Aviado, D.M., 1956. 'Effects of pulmonary embolism on the pulmonary circulation with special reference to arteriovenous shunts in the lung'. Circulation Res. 4, 67-73.

Nims, L.F., 1951. 'Environmental factors affecting decompression sickness'. Chapter 8 in Fulton, J.F., (Ed.).

Noessle, W.F., 1951. 'The significance of fat in sputum'. Am. J. Clin. Path., 21, 430-435.

Odland, L.T., 1959. 'Fatal decompression illness at an altitude of 22, 000 feet'. Aerospace Med., 30, 840-846.

Ogle, J.W., 1857. 'On certain cases in which the foramen ovale was still patent in the adult'. Br. Med. J., 500-501.

Oliver, J., MacDowell, M. & Tracy, A., 1951. 'The pathogenesis of acute renal failure associated with traumatic and toxic injury. Renal ischaemia, nephrotoxic damage and the ischemuric episode'. J. Clin. Invest. 30, 1305-1351.

Owens, G. & Worthington, M., 1962. 'Liver lipid as a source of post-traumatic embolic fat'. J. Surg. Res., 2, 283-284.

Owens, G. & Sokal, J.E., 1961. 'Liver lipid as a source of embolic fat'. J. Appl. Physiol., 16, 1100-1102.

Pallotta, R., 1963. 'Terapia transfusionale nel corso di barotraumi'. Folia med., Napoli, 46, 868-874.

Pallotta, R. & Fati, S., 1962. 'Su alcuni casi di iperpiressia nel corso di barotrauma'. Folia med., Napoli, 45, 866-871.

Paredes, S., Comer, F., Rubin, S., Adler, F. & Peltier, L.F., 1965. 'Fat embolism. Distribution of fat tagged with I^{131} within the body of the rat at various times following intravenous injection'. J. Bone Jt. Surg. 47A., 1216-1220.

Parker, B.M. & Smith, J.R., 1958. 'Pulmonary embolism and infarction'. Am. J. Med., 24, 402-427.

Parsons, F.G. & Keith, A., 1897. 'Seventh report of the committee of collective investigation of the Anatomical Society of Great Britain and Ireland for the year 1896-1897. J. Anat. 32, 164-186.

Parsons, V., 1958. 'A brief review of aviator's decompression sickness and the high altitude decompression test'. J.R. Nav. Med. Serv., 44, 2-13.

Parsons, V., 1959. 'Forced expiratory spirograms following decompression sickness'. Aerospace Med., 30, 821-824.

Pask, E.A., 1942. 'Preliminary note on a method of investigating the site of origin of pain in decompression sickness'. Air Ministry, Lond., Flying Pers. Res. Comm., FPRC Report 484.

Pate, J.W. & Birdsong, S., 1964. 'Carotid air embolism - an experimental study in cats'. Archs Surg., Chicago, 89, 685.

Paton, W.D.M. & Walder, D.N., 1954. 'Compressed air illness - an investigation during the construction of the Tyne Tunnel, 1948-1950'. Med. Res. Council, Spec. Rep. Ser., No. 281.

Patten, B.M., 1938. 'Developmental defects at the foramen ovale'. Am. J. Path., 14, 135-161.

Pecora, L., Mole', R., Rossi, A. & Brancaccio, A., 1965. 'Iperpressione ed enzimi glicolitici'. Folia Med., Napoli, 48, 752-757.

Peirano, J.H., Alvis, H.J. & Duffner, G.J., 1959. 'Submarine escape training experience. Summary of 25 year period July 1929 - Dec 1954'. A.M.A. Archs Ind. Hlth, 20, 106-116.

Pezzi, M., 1937. 'Il volo in alta quota'. Lilienth. forsch. 1937, 52-83.

Philp, C.G., 1937. 'The conquest of the stratosphere'. London, Pitman & Sons, pp. 205.

Philp, R.B., 1964. 'The ameliorative effects of heparin and depolymerized hyaluronidate on decompression sickness in rats'. Can. J. Physiol. Pharmacol, 42, 819-829.

Philp, R.B. & Gowdey, C.W., 1964. 'Experimental analysis of the relation between body fat and susceptibility to decompression sickness'. Aerospace Med., 35, 351-356.

Ploch, W., 1961. 'Beobachtungen bei Unterdruck - höhentod'. Dt. Z. ges. gericht. Med., 51, 420-422.

Poggioli, J.A., 1966. 'Le caisson monoplace dans le traitement des accidents de décompression'. Presse méd., 74, 172-174.

Pol, B. & Watelle, T.J.J., 1854. 'Mémoire sur les effets de la compression de l'air, appliquée au creusement des puits a houille'. Ann. Hyg. publ., 2e ser, 1, 241-279.

Polak, I.B. & Adams, B.H., 1932. 'Traumatic air embolism in submarine escape training'. Nav. Med. Bull, 30, 165-177.

Polayes, S.H., 1953. 'Osseous emboli after spinal tap in a case of Waterhouse-Friedrichsen syndrome complicating pre-eclamptic toxaemia'. Brooklyn Hosp. J., 11, 38.

Popper, H., 1948. 'Significance of agonal changes in the human liver'. Archs. Path., 46, 132-144.

Powell, T.J., Carrigan, E.P. & Stanfield, M.J., 1963. 'Obesity in aircrew'. Aerospace Med., 34, 21-25.

Prinzmetal, M., Ornitz, E.M., Simkin, B. & Bergman, H.C., 1948. 'Arterio-venous anastamoses in liver, spleen and lungs'. Am. J. Physiol., 152, 48-52.

Prior, A.P., 1948. 'The pathology of the liver in deaths from thermal burns'. J. R. Army Med. Cps, 90, 101-108.

RAF Physiological Research Unit, 1941. 'Observations on decompression sickness in man'. Air Ministry, Lond., Flying Pers. Res. Comm., FPRC Report 267.

Rahn, H., Stroud, R.C. & Tobin, C.E., 1952. 'Visualization of arterio-venous shunts by cinefluorography in the lungs of normal dog'. Proc. Soc. Exp. Biol. Med., 80, 239-241.

Rait, W.L., 1952. 'Post decompression shock'. Med. J. Aust.,(ii), 533-534.

Rait, W.L., 1959. 'The aetiology of post-decompression shock in aircrewmen'. U.S. Arm. Forces Med. J., 10, 790-804.

Rangell, L., 1942. 'Cerebral air embolism. The question of arterialization of intravenous air across the barrier of the pulmonary capillaries; report of a case following assumption of the knee-chest position post partum with recovery'. J. Nerv. Ment. Dis., 96, 542-555.

Raphael, S.S. & Lynch, M.J.G., 1958. 'Kimmelstiel-Wilson glomerulonephropathy. Its occurrence in diseases other than diabetes mellitus'. Archs Path., 65, 420-431.

Rapin, M., Goulon, M., Nouailhat, F., Barois, A., Got, C., Henneter, G. & Levy-Allover, M., 1965. 'Quatre cas d'accident neurologique précoce post abortum par embolie gazeuse probable, traités par l'oxygène hyperbare'. Bull. Mém. Soc. Méd. Hôp, Paris, 116, 673-688.

Rappaport, H., Raum, H. & Horrell, J.B., 1951. 'Bone marrow embolism'. Am. J. Path., 27, 407-434.

Rascher, 1942. Translation of letters and reports of experiments in Auschwitz, 1. Height research; 2. Critical research on the damage caused by freezing cold.

Rashbass, C., 1957. 'The aetiology of itching on decompression'. R. Nav. Pers. Res. Comm., Underwater Physiol. Sub-Comm., Report RNP 57/894; UPS 167.

Ratnoff, O.D., 1943. 'The absence of roentgenographically demonstrable bony changes at the hip joint in subjects exposed to simulated high altitudes'. USAAF, School Aviat. Med., Project 201, Report 1.

Renold, A.E. & Cahill, G.F. Jr. (Ed.), 1965. 'Adipose tissue'. Sect. 5 of Handb. Physiol., Washington, American Physiological Society.

Richet, C. Fils, Garsaux, P. & Behague, P., 1927. 'Crises d'épilepsie chez le lapin au cours de la dépression atmosphérique'. Revue neurol., 47, 1076-1078.

Ring, G.C., Blum, A.S., Kurbatov, T., Moss, W.D. & Smith, W., 1961. 'Size of microspheres passing through the pulmonary circuit in the dog'. Am. J. Physiol., 200, 1191-1196.

Rivera, J.C., 1964. 'Decompression sickness among divers: an analysis of 935 cases'. Milit. Med., 129, 314-334.

Robb, H.J., 1963. 'The role of micro-embolism in the production of irreversible shock'. Ann. Surg., 158, 685-692.

Robie, R.R., Lovell, F.W. & Townsend, F.M., 1960. 'Pathological findings in three cases of decompression sickness'. Aerospace Med., 31, 885-896.

Rodbard, S., 1944. 'Recurrence of decompression sickness on reascent to high altitudes'. Air Surg. Bull. 1(xi), 6-7.

Romano, J., Engel, G.L., Webb, J.P., Ferris, E.B., Ryder, H.W. & Blankenhorn, M.A., 1943. 'Syncopal reactions during simulated exposure to high altitude in decompression chamber'. War Med., Chicago, 4, 475-489.

Rosenblum, D.E., 1943. 'The nature and origin of altitude pains'. Am. Rev. Sov. Med., 1, 303-309.

Rosenstiel, 1935. 'Une solution au problème physiologique des hautes altitudes - le scaphandre aérien'. Presse Méd., 43, 1476-1477.

Roxburgh, H.L., 1953. 'Decompression sickness'. Med. Press, 229, 174-178.

Rózsahegyi, I., 1959. 'The late consequences of the neurological forms of decompression sickness'. Br. J. Ind. Med., 16, 311-317.

Rózsahegyi, I. & Kenedi, I., 1961. 'Die Myokardschädigung der Caissonarbeiter'. Arch. Geweberpath. Geweberhyg., 18, 610-631.

Rózsahegyi, I. & Roth, B., 1966. 'Participation of the central nervous system in decompression'. Ind. Med. Surg., 35, 101-110.

Rózsahegyi, I. & Soós, L., 1956. 'Caissonarbeit und Zentralnervensystem'. Arbeitsmedizin, 30, Leipzig, Barth.

Rudolph, S.J., Herring, M.E. & Vavala, D.A., 1961. 'Neurocirculatory collapse associated with reduced barometric pressure'. Aerospace Med., 32, 1023-1025.

Russell, D., 1941, In 'Discussion on fat embolism and the brain'. Proc. R. Soc. Med., 34, 639-656.

Russell, D.C., 1943. 'Clinical observations on selection tests carried out in the decompression chamber'. Air Ministry, Lond., Flying Pers. Res. Comm., FPRC Report 519.

Ryder, H.W., Stevens, C.D., Webb, J.P. & Blankenhorn, M.A., 1945. 'The measurement of decompression sickness'. U.S. Nat. Res. Coun., Comm. Aviat. Med., Report 412.

Sanders, J.H. & Isoe, I.M., 1947. 'Intravenous oxygen and pulmonary embolism'. Ann. Surg., 126, 208-214.

Saunders, W.L., 1891. 'Physical suffering from the effects of compressed air'. Engng Min. J., 52, 119-120.

Schaefer, K.E., McNulty, W.P., Carey, C. & Liebow, A.A., 1958. 'Mechanisms in development of interstitial emphysema and air embolism in decompression from depth'. J. Appl. Physiol., 13, 15-29.

Schmidt, J.H., 1958. 'Fatal bone marrow embolism following thoracotomy'. Am. J. Surg., 95, 94-101.

Schneck, S.A., 1957. 'Decompression sickness at medium altitude'. U.S. Arm. Forces Med. J., 8, 1366-1370.

Schrötter, E. von, 1901. 'Communication d'expériences physiologiques faites pendant un voyage en ballon à 7500 m. et rapport sur différents essais concernant l'étude de l'influence de l'air raréfié sur l'organisme humain'. Archs Ital. Biol., 36, 86-88.

Schrötter, H. von, 1906. 'Der Sauerstoff in der Prophylaxe und Therapie der Luftdruckerkrankungen'. Berlin, Hirschwald. pp. 278.

Seib, G.A., 1934. 'Incidence of the patent foramen ovale in adult American whites and American negroes'. Am. J. Anat., 55, 511-525.

Selkurt, E.E., 1959. 'Intestinal ischaemic shock and the protective role of the liver'. Am. J. Physiol., 197, 281-285.

Sergeyev, A.A., 1962. 'Ocherki po istorii aviatsionaoy meditsiny'. (Essays on the history of aviation medicine). NASA transl. TT-F-176, pp. 412.

Serre, H. & Simon, L., 1959A. 'Aspects cliniques des nécroses parcellaires aseptiques primitives de la tête fémoral chez l'adulte'. Montpell. Méd., 102, 193-210.

Serre, H. & Simon, L., 1959B. 'Infarctus osseux primitif. Rôle de l'athérosclérose'. Sem. Hôp. Paris, 35, 945-948.

Severinghaus, J.W. & Stupfel, M., 1957. 'Alveolar dead space as an index of distribution of blood flow in pulmonary capillaries'. J. Appl. Physiol., 10, 335-348.

Sevitt, S., 1956. 'Distal tubular and proximal tubular necrosis in the kidneys of burned patients'. J. Clin. Path., 9, 279-294.

Sevitt, S., 1957. 'Burns: pathology and therapeutic applications'. London, Butterworth, pp.364.

Sevitt, S., 1962. 'Fat embolism'. London, Butterworth, pp. 253.

Seze, S. de, Jaffres, R., Merer, P., Mitrovic, D. & Mazabraud, A., 1963. 'Aspects histologiques de l'ostéonécrose aseptique barotraumatique'. Sem. Hôp. Paris, 39, 869-878.

Shaw, L.A., Behnke, A.R. Jr, Messer, A.C., Thomson, R.M. & Motley, E.P., 1935. 'The equilibrium time of the gaseous nitrogen in the dog's body following changes of nitrogen tension in the lungs'. Am. J. Physiol., 112, 545-553.

Sherlock, S. & Wolstenholme, G.E.W., 1949. 'Liver disease - Ciba symposium'. London, Churchill.

Shivpuri, D.N., Viswanathan, R., Sharma, M.L. & Singh, P.P., 1959. 'A pre-symptomatic diagnostic sign of venous air embolism'. J. Indian Med. Ass., 33, 86-88.

Shoemaker, W.C., 1967. 'Shock. Chemistry, physiology and therapy'. Springfield, Thomas, pp. 306.

Sicca, U. & Lerza, P., 1954. 'Le fleboclisi clorurosodiche nella terapia delle forme artralgiche della malattia dei cassoni'. Proc. 11th int. Congr. occup. Med. leg. Med., 3, 567-568.

Siebe Gorman & Co., 1886. 'Manual for divers'. London pp. 39.

Sillery, R.J., 1958. 'Decompression sickness. A review of the literature and previously unreported histologic observations'. Archs Path., 66, 241-246.

Simpson, C.K., 1958. 'Delayed death from air embolism in criminal abortion'. Med. leg. J., Lond., 26, 132-134.

Singh, I., 1936. 'Certain effects of pulmonary gas embolism'. J. Physiol., Lond., 87, 11-22.

Slark, A.G., 1962. 'Treatment of 137 cases of decompression sickness'. Roy. Nav. Pers. Res. Comm., Underwater Physiol. Sub-Comm., Report RNP63/1030; UPS 215.

Smith, A.H., 1873. 'The effects of high atmospheric pressure, including the caisson disease'. Prize Essay Alumn. Ass., Coll. Physic. Surg. N.Y., Brooklyn, Eagle Book & Job Printing Dept. pp. 43.

Snell, E.H., 1896. 'Compressed air illness or so-called caisson disease'. London, Lewis, pp.251.

Snyder, J.F. & Duffner, G.J., 1958. 'A methodological test of resistance of divers to decompression sickness'. US Navy Exp. Div. Unit, Res. Rep. 4-59.

Spencer, F.C., Rossi, N.P., Shao-Chi, Y. & Koepke, J.A., 1965. 'The significance of air embolism during cardiopulmonary bypass'. J. thorac. cardiovasc. Surg., 49, 615-634.

Sproull, D.H., 1951. 'Report of a fatality following exposure to high altitude with a review of the pathological aspects of decompression sickness'. Air Ministry, Lond., Flying Pers. Res. Comm., FPRC/Memo 25.

Stevens, A.R., Legg, J.S., Henry, B.S., Dille, J.M., Kirby, W.M.M. & Finch, C.A., 1953. 'Fatal transfusion reactions from contamination of stored blood by cold growing bacteria'. Ann. Intern. Med., 39, 1228-1239.

Stewart, C.B., Bateman, G.L. & Milne, D.J., 1943. 'A comparison of two procedures designed to select airmen resistant to decompression sickness'. Can. Nat. Res. Coun., FPMS Report D-6.

Strel'tsov., 1940. 'The nature of pains developing during high altitude flight'. quoted by Sergeyev, A.A.

Strohl, E., 1932. 'La vitesse d'ascension et de descente en avion - ses effets sur l'organisme'. Thesis, Bordeaux Univ., Paris, Legrand, pp. 45.

Stubbs, R.A. & Kidd, D.J., 1965A. 'A pneumatic analogue decompression computer'. Can. Forces Med. Serv. Report 65-RD-1.

Stubbs, R.A. & Kidd, D.J., 1965B. 'Control of decompression by analogue computer'. Can. Forces Med. Serv. Report 65-RD-8.

Stutman, L.J., 1960. 'An explanation for sudden death in certain flying personnel at high altitude'. Aerospace Med., 31, 659-660.

Sutherland, A.M., 1956. 'Regeneration in the fatty liver of the rat after partial hepatectomy'. J. Path. Bact. 71, 403-408.

Swain, V.A.J., 1942. 'Caisson disease (compressed air illness) of bone with a report of a case'. Br. J. Surg., 29, 365-370.

Swann, H.G. & Rosenthal, T.B., 1944. 'A survey of the incidence of decompression sickness with reference to some constitutional and environmental variants'. USAAF 31st Alt. trng. Unit, Kingman, Arizona, Report 32.

Teare, R.D., 1959. 'Air embolism'. J. Forens. Med., 6, 15-18.

Thomas, D., Stein, M., Tanabe, G., Rege, V. & Wessler, S., 1964. 'Mechanism of bronchoconstriction produced by thromboemboli in dogs'. Am. J. Physiol., 206, 1207-1212.

Thomason, A.T., 1957. 'A case of pulmonary barotrauma with mediastinal emphysema'. J.R. Nav. Med. Serv., 43, 224-228.

Tobias, C.A., 1951. 'Decompression sickness in actual flights'. Chapter 11 in Fulton, J.F. (Ed.).

Tobin, C.E., 1952. 'The bronchial arteries and their connections with other vessels in the human lung'. Surgery Gynec. Obstet., 95, 741-750.

Tobin, C.E. & Zariquiey, M.O., 1950. 'Arteriovenous shunts in the human lung'. Proc. Soc. Exp. Biol. Med., 75, 827-829.

Tobin, C.E. & Zariquiey, M.O., 1951. 'Arteriovenous shunts and blood supply of the bronchi in isolated, injected human lungs'. Anat. Red., 109, 352-353.

Tobin, C.E. & Zariquiey, M.O., 1953. 'Some observations on the blood supply of the human lung'. Med. Radiogr. Photogr., 29, 9-19.

Triger, 1845. 'Lettre à M. Arago'. C.r. hebd. Séanc. Acad. Sci., Paris, 20, 445-449.

Trueta, J., Barclay, A.E., Daniel, P., Franklin, K.J. & Pritchard, M.M.L., 1947. 'Studies of the renal circulation'. Oxford, Blackwell, pp. 187.

Tureen, L.L. & Devine, J.B., 1936. 'The pathology of air embolism: report of two cases'. J. Mo. St. Med. Ass., 33, 141-144.

US Navy, 1962. 'Dysbarism'. Approach, May 1962, 26-28.

US Navy, 1963. 'U.S. Navy Diving Manual'. U.S. Navy Dept., NAVSHIPS 250-538.

US War Dept., 1918. 'Air Service medical manual'. War Dep: Air Serv., Div. Milit. Aeronaut., Wash. D.C. pp. 38.

van Liew, H.D., 1962. 'Oxygen and carbon dioxide permeability of subcutaneous pockets'. Am. J. Physiol. 202, 53-58.

van Liew, H.D., Bishop B., Walder, D. & Rahn, H., 1965. 'Effects of compression on composition and absorption of tissue gas pockets'. J. Appl. Physiol., 20, 927-933.

Vernon, H.M., 1907. 'The solubility of air in fats and its relation to caisson disease'. Lancet, (ii), 691-693.

Vigouroux, R. & Nivelleau, J., 1960. 'Embolie cérébrale gazeuse massive traitée par surpression'. Revue neurol., 103, 485-490.

Villaret, M. & Cachera, R., 1939. 'Les embolies cérébrales. Etudes de pathologie expérimentale sur les embolies solide et gazeuse du cerveau'. Paris, Masson. pp. 134.

Viotti, G. & Walder, D.N., 1965. 'Importanza del tessuto adiposo nell' aeroembolismo disbarico'. Lavor. Med., 19, 1-13.

Wack, J.P., Duboque, T. & Wyatt, J.P., 1958. 'The role of the vertebral venous plexus in the dissemination of labelled emboli'. Archs. Path., 65, 675-680.

Wagner, C.E., 1945. 'Observation of gas bubbles in pial vessels of cats following rapid decompression from high pressure atmospheres'. J. Neurophysiol., 8, 29-32.

Walder, D.N., 1947. 'Serum surface tension and its relation to the decompression sickness of aviators'. M.D. Thesis, Bristol Univ.

Walder, D.N., 1948. 'Serum surface tension and its relation to the decompression sickness of aviators'. J. Physiol., Lond., 107, 43-44P.

Walder, D.N., 1963. 'A possible explanation for some cases of severe decompression sickness in compressed air workers'. in Cunningham, D.J.C. & Lloyd, B.B. (Ed.), 570-572.

Walder, D.N., 1966A. 'Adaptation to decompression sickness in caisson work'. Biometeorology II, 350-359.

Walder, D.N., 1966B. 'Some problems of working in an hyperbaric environment'. Ann. R. Coll. Surg., 38, 288-307.

Walker, W.A., 1940. 'Aseptic necrosis of bone occurring in caisson disease. A case report'. J. Bone Jt Surg., 22, 1080-1084.

Walshe, F.M.R., 1947. 'Diseases of the nervous system'. 5th Ed., Edinburgh, Livingstone, pp. 351.

Wamsley, J.R. & Roberts, J.E., 1963. 'Body composition of USAF flying personnel'. Aerospace Med., 34, 403-405.

Wangensteen, O.H., 1955. 'Intestinal obstructions; physiological, pathological and clinical considerations with emphasis on therapy, including description of operative procedures'. 3rd Ed., Springfield, Thomas pp. 838.

Webb, J.P., Engel, G.L., Romano, J., Ryder, H.W., Stevens, C.D., Blankenhorn, M.A. & Ferris, E.B., 1944. 'The mechanism of pain in aviators' "Bends" '. J. Clin. Invest., 23, 934-935.

Weidner, M.G. & Light, R.A., 1958. 'Role of the autonomic nervous system in the control of the pulmonary vascular bed. III Further studies in experimental pulmonary embolism'. Ann. Surg., 147, 895-901.

Whitaker, D.M., Blinks, L.R., Berg, W.E., Twitty, V.C. & Harris, M., 1945. 'Muscular activity and bubble formation in animals decompressed to simulated altitudes'. J. Gen. Physiol., 28, 213-223.

Whitby, J.D., 1964. 'Early cases of air embolism'. Anaesthesia, 19, 579-584.

Wilson, C.L., 1962. 'Physiological protection of the CSU-4/P high-altitude pressure suit'. USAF Aerospace Med. Res. Lab., Report AMRL-TDR-62-112.

Wilson, C.L., 1965A. 'Wiley Post: first test of high altitude pressure suits in the United States'. Archs envir. Hlth., 10, 805-810.

Wilson, C.L., 1965B. 'Soviet high altitude pressure suit development, 1939-1955'. Aerospace Med., 36, 874-877.

Winkelman, N.W., 1942. 'Cerebral fat embolism. A clinicopathologic study of two cases'. Archs Neurol. Psychiat., Chicago, 47, 57-69.

Wise, D.A., 1963. 'Constitutional factors in decompression sickness'. U.S. Navy, Exp. Div. Unit, Res. Rep. 2-63.

Wittmer, J.F., 1962. 'Pathologic mechanisms in gas and fat embolism'. USAF School Aerospace Med., Aeromed. Rev. 4-62.

Wolf, A. & Siris, J., 1937. 'Acute non-traumatic encephalomalacia complicating neurosurgical operations in the sitting position'. Bull. Neurol. Inst. N.Y., 6, 42-61.

Wolstenholme, G.W.H., (Ed.), 1956. 'Histamine' Ciba symposium. London, Churchill.

Woodward, C.M., 1881. 'A history of the St. Louis bridge; containing a full account of every step in its construction and erection, and including the theory of the ribbed arch and the test of materials'. St. Louis, Jones & Co., pp. 392.

Wright, R.R., 1962. 'Experimental pulmonary hypertension produced by recurrent air emboli'. Medna thorac, 10, 423-427.

Wünsche, O. & Henn, R.H.E., 1962. 'Les conditions de l'embolie graisseuse pendant la décompression'. Paper to 5th Int. Congr. Aviat. Space Med., Madrid.

Zal'tsman, G.L. & Zinov'eva, I.D., 1964. 'Comparative determination of the permissible supersaturation value of the human body with indifferent gases under different conditions'. in Brestkin, M.P. (Ed.), 28-33.

Zambrano, A., Mazza, V. & Anzano, O., 1954. 'Variazioni del quadro protidico e deglo elettroliti nei lavoro dei cassoni'. Proc. int. Congr. occup. Med. Leg. Med., 3, 568-570.

Zamchek, N., Chalmers, T.C. & Davidson, C.S., 1949. 'Pathologic and functional changes in the liver following upper abdominal operations'. Am. J. Med., 7, 409.

Zim, H.S., 1943. 'Man in the air - the effects of flying on the human body'. New York, Harcourt Brace Co. pp. 332.

Index

END

DATE
FILMED

4-82

DTIC