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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AMP Working Group 14

High G Physiological Protection Training

(Accélérations Elevées:
Protection par l'Entraînement)

NORTH ATLANTIC TREATY ORGANIZATION

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

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The material in this publication was assembled to report the results of AGARD Aerospace Medical Panel Working Group 14.

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Preface

The operation of modern, high performance aircraft imposes substantial physiological and mental demands on the pilot. Exposure to the high $+G_z$ loads and rapid rates of G onset that these aircraft are capable of accomplishing has resulted in a number of occurrences of G-induced loss of consciousness (G-LOC). When aircraft recovery was not possible, death of aircrew has occurred.

Concern for the hazards of G-LOC and the other physiological effects of G were addressed at the 40th Business Meeting of the Aerospace Medical Panel (AMP), 6 October 1983, London, United Kingdom. Proposals for Symposia by the Biodynamics and the Special Clinical and Physiological Problems Sub-Committees of the AMP subsequently led to the Symposium: Medical Selection and Physiological Training of Future Fighter Aircrew (AGARD Conference Proceedings No.396) in Athens, Greece, 25—26 April 1985, at which the topic of G-protection training was discussed. At the same Business Meeting, a request by Turkey for "informal" discussions on the topic at its "national half-day" led to the mini-Symposium: Informal Briefings by the F-16 Medical Working Group (AGARD Conference Proceedings No.377) in Istanbul, 27 September 1984, at which some operational experiences in G training of F-16 pilots were presented by members of several NATO nations.

At the 43rd Business Meeting of the AMP, 3 October 1986, Lisbon, Portugal, the Panel accepted a proposal by the Biodynamics Committee to set-up a Working Group that would develop a procedural guide for high-G centrifuge training of aircrew for high performance aircraft. The focus of the Working Group was to review developments in G-protection methods, centrifuge training objectives and indoctrination, centrifuge design performance, and to evaluate the effects of these measures on improving aircrew performance.

The National Delegates Board of AGARD accepted the proposal for this Working Group at its 62nd Meeting in Paris, France, 26—27 March 1987. Working Group 14 — High-G Physiological Protection Training was formed in January 1988 under the Chairmanship of Air Commodore G.K.M.Maat from The Netherlands. Working Group 14 met four times during their two-year mandate. This AGARDograph represents the outcome of their labours.

Jack P.Landolt, PhD
Chairman, Biodynamics Committee
Aerospace Medical Panel

Préface

Les nouveaux avions de combat à haute performance imposent de considérables constraintes physiologiques et psychologiques à leur équipage. Les accélérations élevées et rapidement installées dont sont capables ces avions ont été à l'origine d'un certain nombre de pertes de connaissance (PC-G en anglais G-Loc ou G induced Loss of Consciousness). Lorsque l'avion n'a pu être repris en main, la mort de l'équipage s'en est suivie.

La question des risques des perte de connaissance sous facteur de charge et des effets des accélérations a été examinée durant la 40ème réunion des experts de Médecine Aérospatiale (Panel AMP) de l'AGARD tenue le 6 octobre 1983 à Londres en Grande-Bretagne. Les propositions de symposia faites par les sous-comités "biodynamique", et "problèmes physiologiques et cliniques spécifiques" ont vu le jour avec le symposium intitulé "Sélection médicale et entraînement physiologique des futurs équipages d'avions de combat" à Athènes en Grèce les 25 et 26 avril 1985 (Compte-rendu de la conférence de l'AGARD n° 396). La question de l'entraînement à la protection anti-G y a été examinée. Au cours de la réunion de Londres, la Turquie a proposé que des discussions informelles soient menées durant "sa demi-journée nationale" qui a eu lieu à Istanbul le 27 septembre 1984. Ceci a abouti à un mini symposium ayant pour titre "Exposé libre du groupe de travail médical F 16". L'expérience opérationnelle concernant l'entraînement aux accélérations des pilotes de F 16 a été présentée par plusieurs conférenciers des pays membres de l'OTAN (débats de la conférence AGARD n°377).

A l'occasion de la 43ème réunion du Panel AMP, le 3 octobre 1986 à Lisbonne, Portugal, le Panel a accepté une proposition formulée par le comité de Biodynamique. Il s'agissait pour un groupe de travail d'élaborer, au profit des équipages d'avions à haute performance, un guide de procédures d'entraînement en centrifugeuse aux accélérations élevées. Ce groupe devait faire le point sur les méthodes nouvelles de protection anti-G, les objectifs et les méthodes d'entraînement en centrifugeuse, les caractéristiques des performances des centrifugeuses et présenter le gain de tolérance des pilotes aux accélérations élevées apporté par ces nouvelles méthodes.

Le Conseil des Délégués Nationaux de l'AGARD a accepté la création de ce groupe de travail au cours de la 62ème réunion qui a eu lieu à Paris, France, les 26 et 27 mars 1987. Le groupe de travail n° 14 (WG 14) "Accélérations Elevées: Protection par l'Entraînement" a été créé en janvier 1988 sous la présidence de l'Air Commodore G.K.M.Maat, des Pays-Bas. Le groupe de travail s'est réuni 4 fois durant ses deux années de mandat. Cette AGARDographie représente le fruit de ses travaux.

Jack P.Landolt, PhD
Chairman, Biodynamics Committee
Aerospace Medical Panel

Aerospace Medical Panel

Chairman: Mr C.Bates, Jr
Director
Human Engineering Division
AAMRL/HE
Wright-Patterson AFB
OH 45433-6573
United States

Deputy Chairman: Med en Chef G.Santucci
Chef du Laboratoire Central de
Biologie Aérospatiale
C.E.R.M.A.
Base d'Essais en Vol
91228 Brétigny sur Orge
Cedex
France

WORKING GROUP 14 MEMBERS

Dr F.Buick
DCIEM
Biosciences Division
1133 Sheppard Ave. W.
P.O. Box 2000
Downsview, Ontario M3M 3B9
Canada

Med. Principal J.M.Clère
Laboratoire de Médecine Aérospatiale
Centre d'Essais en Vol
B.P. 2
91220 Brétigny Sur Orge
France

Lt Col. G.J.T.Hoekstra, RNLAF (Ret.)
Netherlands Aerospace Medical Centre
P.O. Box 22
3769 ZG Soesterberg
The Netherlands

Air Cdre G.K.M.Maat, RNLAF (Ret.)
Netherlands Aerospace Medical Centre
P.O. Box 22
3769 ZG Soesterberg
The Netherlands

Dr R.Burton
USAFSAM/CA
Brooks AFB, TX 78235-5301
United States

Group Captain D.H.Glaister
Head of Biodynamics Division
RAF Institute of Aviation Medicine
Farnborough, Hants GU14 6SZ
United Kingdom

Col. T.S.Johansen, MD
Director Aeromedical Services
Danish Defence Command
P.O. Box 202
DK-2950 Vedbaek
Denmark

Mr L.Meeker
Chief, Systems Engineering Branch
USAFSAM/VNS
Brooks AFB, TX 78235-5301
United States

PANEL EXECUTIVE

Major W.D.Lyle

Mail from Europe:
AGARD—OTAN
Attn: AMP Executive
7, rue Ancelle
92200 Neuilly sur Seine
France

Mail from US and Canada:
AGARD—NATO
Attn: AMP Executive
APO New York 09777

Telephone: 33(1) 47 38 57 60
Telex: 610176 (France)
Telefax: 33(1) 47 38 57 99

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Introduction and Recommendations

The purpose of this book is to give a concise and complete picture of the accelerative forces encountered in high performance aircraft, their effects upon the crew and the countermeasures that should be taken. The training possibilities and equipment now and in the future, are dealt with extensively; although, for those readers whose interest extends even further a list of titles is suggested.

The chapters, each with a summary, are placed in a logical sequence; nonetheless, some chapters may be consulted separately.

After a general introduction wherein the three main subjects: G-forces, G-effects and G-training are placed in a historical context, the second chapter offers the scientific basis for the G-concept. ~~To understand the fundamentals, reading of this chapter is essential~~.

Chapter 3 is of a more applied nature: the human tolerance of G-forces and the different ways of measuring it are discussed. The chapter continues with a description of the standard G-protection methods: the suits, the valves and the complete details of the Anti-G Straining Maneuver. Logically the potential G-protection methods are treated in the next chapter. ~~Much attention is given to positive pressure breathing as a G-protective method, thus named PBG.~~

A complete chapter (5) is dedicated to the intriguing but very dangerous phenomenon of G-induced loss of consciousness, that in fact has convinced the airforces to make centrifuge training mandatory.

The human centrifuges available in NATO are discussed in detail in chapter 6. Very interesting general data on the centrifuge such as definitions, performance, safety and design features, are brought together in this chapter.

A chapter on fitness geared to acquiring a higher G-tolerance is included as chapter 7, which discusses aerobic and anaerobic exercise regimes and life-style considerations.

The actual conducting of centrifuge training, in the form of a "cookbook", the reader finds in chapter 8.

Apart from the impressive 220 references, the book closes with chapter 9 on training applications and standards, ~~the discussion therein leads up to the following recommendations and conclusions~~.

- *G-protection techniques should be instructed and trained in a simulated high G-environment i.e. a proper human centrifuge.*
- *Aircrew should undergo this training before they encounter 5 G_z in the cockpit in order to prevent them learning a wrong coping technique.*
- *Aircrew should be retained in case of transfer to a high G-aircraft, after absence from high G-flying for more than six months and after an illness, the latter subject to medical judgment.*
- *The value of routine retraining is still debatable.*
- *Improved equipment and modern techniques as PBG are essential to increase G-Tolerance.*

Δ (25) * Flight training, * Protective equipment, * Stress (Physiology), NATO.

Introduction et Recommandations

Le but de ce manuel est de donner un aperçu concis des effets des accélérations rencontrées sur les avions de combat à haute performance mais aussi d'exposer l'ensemble des moyens de protection anti-G à la disposition des pilotes. Les différents volets de l'entraînement et des équipements actuels ou futurs sont présentés de façon exhaustive. Enfin, pour les lecteurs en quête d'informations, de nombreux articles sont référencés à fin de ce manuel.

Les chapitres sont présentés dans un ordre logique mais peuvent être lus séparément.

Après une introduction générale présentant trois thèmes (forces d'inerties, effets, entraînement) dans leur contexte historique, le second chapitre traite des bases théoriques du concept des accélérations. La compréhension de ce chapitre est particulièrement importante.

Le chapitre 3 est beaucoup plus appliqué; la tolérance humaine aux accélérations $+G_z$ et les différentes manières de la mesurer y sont discutées. Ce chapitre se poursuit par la présentation des méthodes classiques de protection anti-G: panatalon et valve ainsi que manoeuvre anti-G. Logiquement, les méthodes de protection anti-G potentielles (voire futures) sont traitées dans le chapitre suivant. La respiration en pression positive sous facteur de charge (nommée en anglais PBG — Positive breathing during G) est particulièrement développée.

Un chapitre complet (5) est dédié à un phénomène particulier et très dangereux, la perte de connaissance sous facteur de charge (PC-G). Ce phénomène a convaincu les Armées de l'Air de nombreux pays de la nécessité d'entraîner leurs pilotes en centrifugeuse.

Les centrifugeuses utilisées dans le pays de l'OTAN sont présentées en détail dans le chapitre 6. De très intéressantes données concernant les centrifugeuses d'entraînement sont exposées avec en particulier la définition et les caractéristiques des performances ainsi que celles des systèmes de sécurité.

Le chapitre 7 décrit l'entraînement physique nécessaire á l'acquisition d'une meilleure tolérance aux accélérations. L'intérêt d'un entraînement musculaire aérobie ou anaérobie est discuté, ainsi que des considérations sur l'hygiène de vie.

Le chapitre 8 présente la méthode préconisée à ce jour pour l'entraînement en centrifugeuse. Ceci est fait de façon claire et précise comme une recette de cuisine.

Les impressionnantes 220 références mises à part, le chapitre 9 termine ce manuel sur les normes et règles d'entraînement. Il en ressort les recommandations suivantes:

- *Les techniques de protection anti-G devraient être enseignées à l'aide d'un simulateur d'environnement à haut facteur de charge, en deux mots une centrifugeuse humaine.*

- *Les pilotes devraient être soumis à cet entraînement avant d'être exposés en vol à des accélérations supérieures à 5 G pour éviter qu'ils n'apprennent une mauvaise technique de manoeuvre anti-G.*

- *Les pilotes devraient être réentraînés dans les cas suivants: lorsqu'ils accèdent au pilotage d'avion à facteur de charge élevé, après avoit interrompu pendant une durée supérieure à six mois le vol sur ce type d'aéronefs, après une maladie, à la demande du médecin du personnel navigant.*

- *Le délai entre deux entraînements reste encore un sujet à débattre.*

- *L'amélioration des équipements et des techniques de protection anti-G tels que la surpression respiratoire sous facteur de charge est importante pour diminuer la fatigue liée à une exécution correcte d'une manoeuvre anti-G.*

CHAPTER 1
HISTORICAL ASPECTS OF HIGH-G CENTRIFUGE TRAINING

INTRODUCTION

A treatise on high-G physiological protection training must be primarily concerned with three topics over and above centrifuge G training: (a) G-induced loss of consciousness (G-LOC) — the reason for the training requirement; (b) the anti-G straining maneuver (AGSM) — the focus of the training; and (c) the centrifuge — the equipment that is required for the training. In this first chapter, these three topics are briefly discussed relevant to the subject of centrifuge G training, along with a review of their interesting histories.

G-INDUCED LOSS OF CONSCIOUSNESS (G-LOC)

G-LOC is defined as "a state of altered perception, wherein (one's) awareness of reality is absent as a result of sudden critical reduction of cerebral blood circulation caused by increased G force" (39). This description separates G-LOC from G-induced visual impairment (i.e., grayout or blackout) with the phrase "awareness of reality is absent"—a critical difference between these two G hazards. G-LOC is particularly more hazardous than the light loss phenomenon, not only because awareness of reality remains with blackout, but also because of different recoveries; i.e., blackout recovery is immediate, and G-LOC requires an average of about 30 seconds before the pilot is capable of flying the aircraft.

G-LOC of pilots, then called "fainting in the air," first occurred in World War I (WW I) and may have been, even then, the cause of some military aircraft accidents (106). The potential hazards of G-LOC in the more modern, high performance aircraft were first discovered by Dr. W. K. Stewart, while conducting research on the subject in fighter aircraft for the Royal Air Force at the beginning of World War II (WW II). However, despite photographic evidence of G-LOC episodes in aircraft, the UK Flying Personnel Research Committee dismissed the "problem" by declaring that: (a) such episodes were "entirely typical of many aircrew"; and (b) unsuccessful pilots (certainly including those who suffered G-LOC) had already been shot down (105).

Hence, G-LOC was not recognized as a major military flying threat until its hazards were once again documented in 1978 by videotapes of its occurrence in subjects on the centrifuge (211), and by pilots' reports of near-mishaps due to G-LOC in F-15 aircraft during air combat tactics evaluations and air combat training (154). This documentation of the hazards of G-LOC, along with anonymous survey data of pilots suffering G-LOC during increased G maneuvers, clearly identified a potential military problem (158). This potential problem quickly became an actual problem, especially for US Air Force pilots, when major accidents of high performance aircraft were verified as being caused by G-LOC (52).

ANTI-G STRAINING MANEUVER (AGSM)

The anti-G straining maneuver (AGSM) (see Chapter 3) is a technique for increasing blood pressure and, therefore, essential for withstanding the high sustained G in modern aircraft. A type of AGSM useful in flight was first discovered as a method to increase G tolerance by Stainforth of England in 1933 (194). He found that straining the abdominal muscles increased G tolerances 2 G, from 4 to 6 G. He also observed that the breath should not be held under this condition, since it would interfere with venous return. Early in WW II, the Germans trained Stuka dive bomber aircrew to strain their abdominal muscles as an anti-G method by encouraging them to learn and practice ski jumping. The AGSM was developed for use by pilots of fighter aircraft at the Mayo Clinic by Dr. Earl Wood and his colleagues, conducting acceleration research during WW II (213,216). They determined the physiologic basis of the pulmonary aspects of a type of AGSM called the M–1 (for maneuver 1), and developed a method to teach it to pilots (214). The M-1, very efficiently and rapidly develops an increased intrathoracic pressure using a partially closed glottis. This type of AGSM was commonly used by pilots during WW II.

In the early 1970s, the USAF F-15 aircraft, with sustained 9-G capability, was about to become operational. At that time, the USAF School of Aerospace Medicine (USAFSAM) was tasked to determine the high sustained G (HSG) tolerance capability of the human. Several physiologic studies were conducted (46) which showed that the human could be instructed in performing an AGSM to increase G tolerances to 9 G, for 45-seconds duration, while wearing an inflated anti-G suit (157).

Following these studies, a formalized method was developed to train pilots on the centrifuge to perform an effective AGSM that advocated the L-1 (Leverett) technique. The L-1 is preferred by most pilots over the M-1, because intrathoracic pressure of the L-1 is developed with a completely closed glottis, and produces less throat irritation during exhalations than with the partially closed glottis of the M-1 (174). This G-training program, which was developed and made available for transition to USAF operations in 1978, was not adopted until 1983, using the USAFSAM human-use centrifuge. At this same time, The Netherlands began centrifuge training in Soesterberg for the Royal Netherlands Air Force (RNLAF) and the United States Air Force Europe (USAFE) (187). The Japanese began pilot centrifuge training even earlier in 1982 (168). The USAFSAM training method (or one very similar) is now in use in several countries, some of which have built centrifuges solely for the purpose of teaching the AGSM.

CENTRIFUGES

A centrifuge, with a continuously changing direction at the same speed, produces sustained uniform acceleration (see Chapter 6 for more detail). Hence, accelerations developed by aircraft can be closely reproduced by using centrifuges. They are, therefore, the principal tool for research (aside from aircraft) in sustained acceleration phenomena. Centrifuges not only provide precise and repeatable acceleration fields, but also allow observation and contact with subjects. In addition, they permit more sophisticated physiologic measurements than can be achieved in flight, because aircraft safety and ejection concerns are non-existent in the centrifuge.

Also of practical importance is the fact that centrifuges are capable of following a complex G-profile typical of aerial combat maneuvers (ACM) (Fig. 1-1). Such a simulated ACM (SACM) pattern has periods of high and low G. The high-G periods correspond to maneuvering advantages for offense or defense. Low-G periods represent conditions favorable for firing weapons. For these same reasons, the centrifuge is an ideal instrument for teaching pilots how to perform an effective AGSM in complete safety.

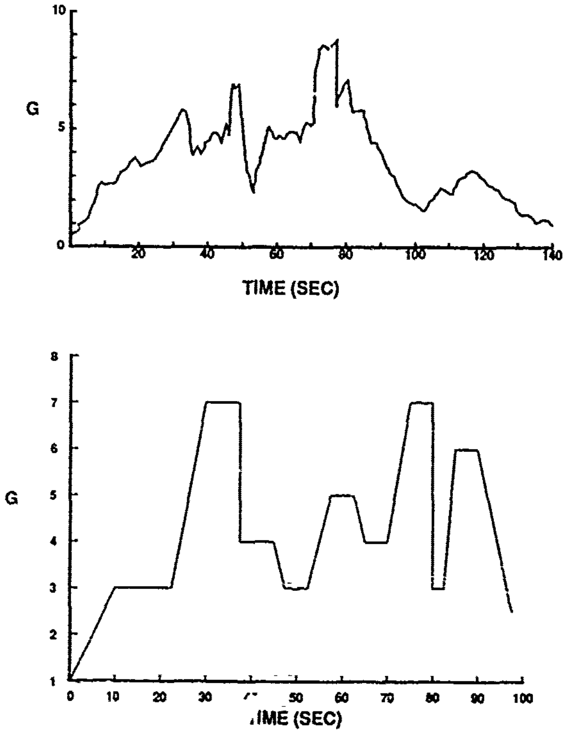

Fig. 1-1
Actual accelerometer tracing of an F-4 aircraft in an air-to-air aerial combat engagement with another F-4 is shown in upper. Aerial combat maneuvering G profile used in a centrifuge exposure simulating the F-4 engagement is shown in lower.

Early History of Centrifuges

As early as 1795, acceleration forces sustained for several seconds to minutes were generated by "centrifuges." The first use of centrifugation was told to Erasmus Darwin, grandfather of Charles, as a method of inducing sleep in a man lying across a stone wheel used to mill corn. He suggested that the centrifugal force accumulated blood in both head and feet, compressing the brain (212).

Centrifuges became relatively common in the early nineteenth century, primarily to treat mental illness. These machines were capable of either positive or negative 5 G, depending on the positioning of the patient. By the mid-1800s, many of the more significant physiologic effects of acceleration were known by physicians who used themselves as subjects on centrifuges. The knowledge they gained from their studies—about the effects of G on respiration, heart rate, and blood distribution — was used to treat various circulatory disorders.

In 1873, Professor E. J. Marey, of Le College de France, built a rotating machine to observe the flight of birds in harnesses. His student, Salathe, turned the machine into a centrifuge which he used to study the effect of acceleration on the physiology of animals. By this time, Ernst Mach, Austrian physicist, had deduced that gravity and centrifugal forces were equivalent. Hence, Salathe was the first physiologist specifically to determine their equivalence for the cardiovascular system. With this knowledge, he soon realized that he could reproduce some of the effects of orthostasis on the centrifuge.

In 1898, Dr. F. R. von Wenusch built a centrifuge with a 7-ft diameter which he used for human experimentation (Fig. 1-2). One of his subjects, who had a slight hangover, went to sleep on the centrifuge after 15 min at 50 rpm, thus experiencing -3 G_z at the head and +3 G_z at his feet.

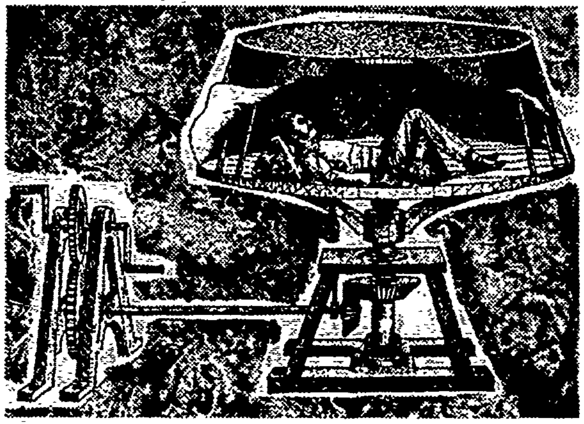

Fig. 1-2
Centrifuge used by von Wenusch. From W.J. White (212)

In 1903, Sir Hiram Maxim built a captive flying machine as an attraction at fairs, the year that the Wright brothers first tested their airplane at Kitty Hawk. His chief engineer, Dr. A. P. Thurston, was the first to test the machine; but at 6.87 G he became unconscious, and regained consciousness only after the machine had been slowed to 3 G. This appears to be the first documented case of G-induced loss of consciousness (G-LOC), a condition that now concerns pilots of high performance aircraft.

History of Research Centrifuges

As early as WW I, problems of pilots' limitations to G tolerance were recognized, and were incriminated in aircraft crashes (106). Concern that these crashes might have been caused by G, since pilots were pulling 5.5-9 G at speeds of 320 km/hr, prompted Drs. A. Broca and P. Garsaux in 1918, in France, to conduct some animal experiments using a 6-m diam. centrifuge (25). They chose dogs because these were "closely" the size of the human. They considered quite correctly that size was an important factor because they were concerned about organ compressions and the problem of dimensions—"it is the conflict of squares against cubes"—that involves the basic concepts of similitude.

Their experiments were conducted at 20, 30, 40, and 98 G, using 5-min exposures. Death only occurred during the 98-G exposure, so they ran a dog at 80 G for 2 min and it survived. On the autopsy of the dog that died at 98 G, they found considerable blood congestion in the abdominal area that prompted them to suggest the use of an abdominal belt for support (Probably the first idea for an anti-G suit!).

From these studies they concluded that human death from flight was not caused by centrifugation; but, they were concerned about a "decrease of nervous reaction" (Possibly alluding to G-LOC?). They proposed to study this phenomenon next using humans on a centrifuge. In 1926, Dr. Garsaux attempted this G study with his new centrifuge, designed to test airplane wings, that was 54 ft in diameter. But it was underpowered for G-tolerance studies and could not exceed 2.5 G (18).

About this time, in the 1920s, pilots in various air races in the U.S. routinely reported blackout and LOC which clearly provided the incentive to study systematically the physiologic effects of G. These early experiments were conducted in aircraft, because human-use centrifuges had not yet been built (193).

The first centrifuges used for controlled physiologic experimentation on acceleration forces related to flight problems were designed and built by the Diringshofen brothers for The Netherlands and Germany about 1933 (28). Basic cardiovascular research using rabbits was conducted on the Dutch centrifuge. On the other hand, human research was primarily undertaken on the German centrifuge.

This German centrifuge had a diameter of 5.4 m and was capable of at least 15 G. Human studies, conducted with subjects in various positions, determined G tolerances and identified G-LOC, blackout, and minute skin hemorrhages (petechiae). These studies also found that reducing the head-seat height made the hydrostatic forces smaller and offered sizable increases in human G tolerances. Their research identified the need for some form of G protection about 6 G in "high-power aircraft," thus suggesting the possible development of an automatic reclining (swivel-type) seat (192).

The first U.S. centrifuge studies used human subjects, and were conducted by Drs. Armstrong and Heim in 1938, employing a 20-ft radius centrifuge powered by a 25-hp electric motor at the Physiological Research Laboratory, Wright Field, Dayton, Ohio. The research conducted on this apparatus was the basis for the first physiologic review published in the U.S. "The Effect of Acceleration on the Living Organism" (6).

The early part of WW II clearly demonstrated the value of high performance aircraft in warfare, and the limitations of the pilot to G. The need to know more about the physiologic effects of G on the human body, particularly as they pertained to the development of protective measures against G, became apparent. Centrifuges were quickly built for these studies in the U.S., Australia, and Canada. By the end of WW II, six Allied centrifuges were in operation:

1. Royal Canadian Air Force Accelerator Unit, Toronto, Canada.
2. Royal Australian Air Force, Flying Personnel Research Unit, Sydney University, Australia.
3. U.S. Army Aeromedical Laboratory, Wright Field, Ohio.
4. University of Southern California, Los Angeles, California.
5. Naval Air Station, Pensacola, Florida.
6. Mayo Aeromedical Unit, Rochester, Minnesota.

On the other hand, beginning in 1940, the British had studied the problem of G in pilots flying aircraft, but without the aid of a centrifuge, primarily because of cost considerations (105), a situation which was corrected when a centrifuge was built in Farnborough, U.K., in the early 1950s.

The intensity of $+G_z$ research subsided after WW II, leading to the deactivation or destruction of all of these centrifuges, only to be rekindled within the last two decades by the advent of high performance aircraft with 9 G capabilities and the problem of G-LOC. At the present time, acceleration research and centrifuge pilot training are conducted in several countries, all using centrifuges built or greatly modified after WW II.

Because only high performance military aircraft (except for a few aerobatic aircraft) routinely develop accelerative forces that exceed man's tolerances, the vast majority of aeromedical and physiologic research on G forces in the U.S. is currently conducted in three Department of Defense (DOD) laboratories and one NASA laboratory using modern high-performance centrifuges. In addition to the U.S., the following other NATO countries have modern human-use centrifuges for conducting research: The Netherlands, Germany, France, Great Britain, Canada, and Turkey (see Chapter 6).

History of G-Training Use Centrifuges

The human-use centrifuge, although serving for several decades as a research tool, has only recently found the applied use of training aircrew to perform an effective AGSM during exposures to G. Although briefly considered after WW II as a training aid for educating recruits in the unique feel of the G forces that they would experience during flight, the centrifuge was not at that time adopted as a routine training device.

The first dedicated training program using a centrifuge was conducted with NASA using the 50-ft radius high-G onset rate centrifuge at the Naval Air Development Center (NADC), Warminster, Pennsylvania. Mercury astronauts were trained up to +12 G_x, simulating launch and reentry profiles. In 1962, D. K. Slayton stated that, "We feel that the centrifuge has been one of our most valuable training devices." In 1965, a large centrifuge was constructed at the Johnson Space Center, Houston, Texas, and was used as a training device by suspending astronauts from its arm to simulate locomotion on the moon at 1/6 G.

Pilot training using a centrifuge began at USAFSAM in 1964 for student pilots from the Aerospace Research Pilot School (ARPS), Edwards AFB, California. Pilots who would be selected as astronauts for the USAF Manned Orbiting Laboratory (MOL) Program, or as X-15 test pilots, had to be graduates of ARPS. For these ARPS student pilots, a 3-week course: "Bioastronautics for Space Research Pilots," taught at USAFSAM, involved centrifuge training. Over 240 ARPS students were trained at USAFSAM before the program at Edwards AFB was terminated.

In 1971, the Commander of the Tactical Air Command (TAC) approved high G training for F-4 pilots assigned to the Fighter Weapons Instructor Course at Nellis AFB, Nevada. This training, which commenced in 1972, involved lectures, demonstrations, and exposure to HSG and a SACM (Fig. 1-1). Ninety-four F-4 aircrew were trained before the program was terminated in 1973. Pilot acceptance of this early centrifuge training program was generally high (135).

Early in the 1970s, immediately before the F-15 became operational, concern developed in the USAF operational community regarding the limited G tolerance of pilots flying aircraft capable of sustaining 9 G. Scientists at the acceleration laboratory at USAFSAM became similarly concerned after a high-G study was conducted which clearly showed that the human is capable of 9 G only if an extremely effective AGSM is performed. Consequently, to address the potential danger to pilots of high-G maneuvering when they did not know how to perform an adequate AGSM, USAFSAM developed during the mid-1970s an advanced high-G training program for TAC pilots. This program included lectures on high-G hazard, physiology of G stress, and means of protecting against the effects of high-G stress, and was to have included centrifuge exposures to demonstrate individual G tolerance and develop proficiency in the AGSM. Although the centrifuge training was not implemented until later, the didactic portion of the program was carried to USAF operational units, 1978-1979, by USAFSAM scientists who traveled to numerous Air Force bases to brief pilots on G stress and protection. To further aid the dissemination of this critical information, the lectures were videotaped and distributed with other visual aids to TAC flight surgeons and aerospace physiologists, so that they could help the pilots become more aware of the need and of the proper technique for doing an AGSM. In early 1983, the evidence that fatal USAF aircraft mishaps were being caused by G-LOC became so clear that TAC commanders decided to implement a number of procedures to try to prevent such mishaps. One of these was another vigorous educational effort involving videotapes and "road shows." The more significant occurrence, however, was that TAC instituted high-G centrifuge training. The first group of TAC pilots received this training on the USAFSAM centrifuge in April 1983, and in 1988, the first centrifuge dedicated to pilot training in the U.S. was built for Lead In Fighter Training (LIFT) at Holloman AFB, New Mexico.

High-G centrifuge training is now a well-established method in the attempt to minimize the occurrence of G-LOC in high performance aircraft, with such training now being conducted not only at Holloman AFB for TAC pilots, but also at Soesterberg for seven NATO countries and USAFE, Korea, Sweden, and in Japan for Pacific Air Forces (PACAF) pilots (168,187). Several other countries and the US Navy are planning to acquire centrifuges for high-G training.

High-G physiological protection training involves the use of a centrifuge to teach pilots of high performance aircraft to safely perform an effective AGSM. This AGSM is required to increase human tolerance to high G so as to prevent the occurrence and potential hazards of G-LOC (see Chapter 8).

SUMMARY

G-induced loss of consciousness (G-LOC) is defined as "a state of altered perception, wherein (one's) awareness of reality is absent as a result of sudden critical reduction of cerebral blood circulation caused by increased G force." G-LOC, then called "fainting in the air," was first recognized as a cause of military aircraft accidents in World War I. In World War II (WW II), blackout, and to some extent G-LOC, was considered a major problem for Allied fighter pilots that resulted in the development of an anti-G straining maneuver (AGSM) and an anti-G suit to increase G tolerance. These two G countermeasures are still today the principal means of increasing G tolerance for pilots of high performance aircraft. Centrifuges used to expose humans to acceleration date back to 1795. Centrifuges for research purposes, using humans as subjects, first occurred in the early 1930s in Germany. During WW II, the Allies had six centrifuges conducting acceleration research. Centrifuge G training began in 1962 to train U.S. astronauts in the Mercury Program. Pilots of military aircraft first began centrifuge training in 1972 at the USAF School of Aerospace Medicine (USAFSAM) where ninety-four F-4 aircrew were trained in performing the AGSM. This program was terminated in 1973. Training of fighter pilots on the centrifuge on a regular basis was resumed at USAFSAM in 1983 after G-LOC was recognized as a significant cause of mishaps of high-performance aircraft. Now many countries use the centrifuge routinely for pilot training of the AGSM and is the main subject of this AGARDograph.

ASPECT THEORIQUE DE L'ENTRAINEMENT EN CENTRIFUGEUSE AUX ACCELERATIONS ELEVEES.

La perte de connaissance liée aux accélérations (PC-G en anglais G-LOC) peut être définie comme "un état de conscience" modifié de façon telle que la réalité n'est plus perçue. Ceci est lié à une diminution majeure et subite de la circulation cérébrale due à l'augmentation de l'accélération de la pesanteur". La PC-G appelée alors "perte de conscience en vol" a été identifiée, pendant la première guerre mondiale, comme étant la cause de certains accidents survenus aux avions militaires. Pendant la deuxième guerre mondiale, le voile noir et dans une certaine mesure, la PC-G, ont posé un problème majeur aux pilotes de chasse. Ceci a eu pour conséquence le développement d'une manoeuvre anti-G et d'une combinaison anti-G. Aujourd'hui encore, ces deux moyens restent les principales méthodes utilisées pour améliorer la tolérance aux accélérations $+G_z$ des pilotes d'avions à haute performance. Des centrifugeuses humaines ont été employées dès 1795, mais les premières expérimentations humaines ont débuté dans les années 1930 en Allemagne. Pendant la deuxième guerre mondiale, les alliés avaient six centrifugeuses pour mener des expérimentations concernant les effets des accélérations. L'entraînement en centrifugeuse a commencé en 1962 aux Etats-Unis dans le cadre du programme spatial Mercury. L'entraînement à la manoeuvre anti-G a débuté au profit de 94 pilotes de F4 de l'U.S. Air Force en 1972 à l'Ecole de Médecine Aérospatiale de l'USAF (School of Aerospace Medicine ou USAFSAM). Ce programme s'est terminé en 1973. Le nombre croissant de PC-G sur avions à haute performance responsable d'accidents a amené à reprendre cet entraînement de façon régulière à partir de 1983. A ce jour, l'entraînement des pilotes à la manoeuvre anti-G est mené de façon régulière par de nombreux pays. Cet entraînement est le sujet de cette ARGARDographie.

CHAPTER 2
PHYSICS AND PHYSIOLOGY

INTRODUCTION

Newton's first law of motion states that a body will remain in a state of rest or of uniform motion in a straight line unless acted upon by a force. A prime principle of successful air combat must be the antithesis of such 'sitting duck' behaviour and, in line with this, current aircraft technology permits the application of high and sustained forces in order to achieve the desired rapid changes in velocity. The physics of these forces, and the body's mechanical and physiological responses to them, form the subject matter of this chapter.

Velocity is a vector quantity having properties of both magnitude (speed) and direction (bearing) and, as stated above, a change in either requires the application of a force. The fundamental unit of force in SI units is the newton (N) - the weight of a mass of one kilogram under standard conditions of gravity. Acceleration is the rate of change of velocity, and is thus also a vector quantity. It is related to the applied force according to Newton's second law, usually expressed as:

$$\text{Force} = \text{mass} \times \text{acceleration}.$$

Mass, being the quantity of matter concerned, remains constant, so that accelerations lead to changes in weight. This is simply perceived when one tries to maintain head position, or raise an arm, during exposure to acceleration, but less apparent is the effect of the weight of the blood in the cardiovascular system, or the weight of the lungs within the thorax.

The definition of the newton implies that accelerative forces can be measured in multiples of the standard gravitational acceleration. This is a useful practice as the baseline condition of 1g, a gravitational acceleration of 9.81 ms^{-2}, is what we are all familiar with, rather than the weightlessness of free fall. Thus:

$$G = \frac{\text{applied acceleration in } ms^{-2}}{\text{standard acceleration of gravity } (9.81 ms^{-2})}$$

Newton's third law of motion states that for every action (or force) there is an equal and opposite reaction (or inertia): it is this inertial reaction which is sensed and which affects human physiology. This distinction will be clarified by considering the special case of centrifugal acceleration.

The forces on a subject produced by a centrifuge are identical to the forces experienced by the crew of a maneuvering aircraft. Although as stated above, these forces are typically expressed in units of G, they have only partly to do with gravitational force as such. For an earth based centrifuge, or an aircraft operating nearby, there is an ever present acceleration acting on the object in a line directed through the centre of the earth. This acceleration acting on the mass of the object produces a force acting along the same line, according to Newton's second law, and gives the mass "weight." When the centrifuge is motionless the only force acting on the subject in the gondola is the acceleration of gravity, or weight.

When the centrifuge is revolving at a constant angular rate, the gondola is restrained from moving in a straight line, as Newton's first law predicts, by the centrifuge arm which applies a centripetal (or centre seeking) acceleration and holds the gondola motion in a curved path (Fig. 2-1). Since the velocity of the gondola is a vector quantity made up of both speed and direction, the change in direction with respect to time results in an acceleration along the axis of the centrifuge arm according to Newton's second law. The product of the equal and oppositely directed acceleration and mass is, according to Newton's third law, the centrifugal force experienced in a centrifuge.

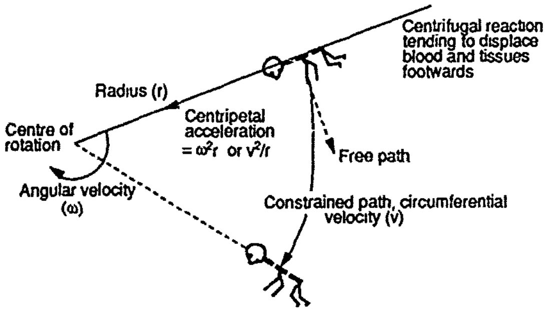

Fig. 2-1

Factors concerned in the generation of +Gz centripetal acceleration and its equal and opposite centrifugal reaction. The body is constrained to follow a circular path with the head towards the centre of rotation.

The magnitude of this acceleration, and of the equal and opposite inertial force, is given by the square of the circumferential velocity divided by the radius:

$$\text{Centripetal acceleration } (ms^{-2}) = \frac{\text{velocity}(ms^{-1})^2}{\text{radius (m)}}$$

Each component of the body of a subject seated in the centrifuge gondola must likewise be constrained if it is to follow the same circular path, and it is the displacement of relatively mobile and unrestrained tissues which is sensed as the equal and opposite inertial reaction, or centrifugal (centre fleeing) acceleration. Displacement of the otoliths due to their increased weight, or the increased pressure on the buttocks due to increased body weight, allows us to judge the level of centrifugal force (or G), while displacement of blood within distensible vessels is a major factor in determining the body's G tolerance.

An aircraft flying in a circular path produces an analogous situation except that a given level of acceleration will usually be attained using a larger radius and circumferential speed than in an earth-bound centrifuge. The vector sum of the radial G and weight, (the mass of an object times the earth's gravitational constant), then describes the total force acting on the subject. It may be noted at this point that we are adding the vectors of two different kinds of forces, gravity and centrifugal. Centrifugal force was described earlier as the reaction to the centripetal force provided by the centrifuge arm, but gravity is a different thing entirely. Although Newton quantified the effect of gravity in his Universal Gravitational Law, he did not postulate the nature of the gravitational force. Einstein proposed, in his General Theory of Relativity, that gravitational force was produced by a disturbance in space-time around matter. Fortunately, however, in his Principle of Equivalence, Einstein stated that the forces produced either by gravitation or by motion on any particular object are completely equivalent, and this has been verified by experiment to be true to at least one part in 10^{11}. It is because of this Principle of Equivalence that the vectors from these two different forces may be added. Interested readers are directed to reference 177 for a detailed introduction to gravitational biology.

Being equal and opposite to the vector quantity of centripetal acceleration implies that centrifugal acceleration also comprises two components - magnitude and direction. Both are important parameters when considering the asymmetries and non-isotropic behaviour of human tissues, and it is essential to define them clearly and unequivocally. Confusion has been avoided by the international adoption of the three-coordinate system of nomenclature introduced by Gell (83). This is illustrated in figure 2-2 which shows the directions and nomenclature of the resulting inertial reactions for the three major body axes.

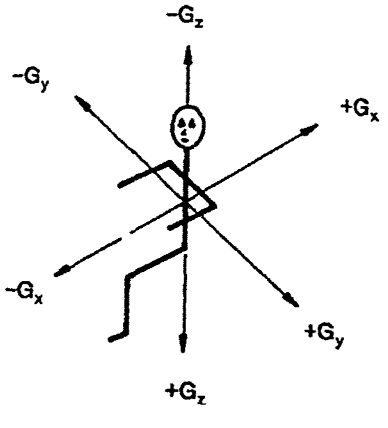

Fig. 2-2
Standard acceleration nomenclature. The arrows indicate the direction of the inertial reaction to an equal and opposite acceleration.

Additional descriptors are given in table 2-1, which includes the readily appreciated astronaut's terminology based upon the intuitive inertial reaction of the eyeballs. While this terminology is adequate for most purposes, further details are needed to define the precise posture adopted by a subject exposed to acceleration such factors as head position (for a reclined subject) or foot position (for a seated subject) can have a considerable bearing on acceleration tolerance and symptomatology.

Table 2-1

Nomenclature of acceleration and inertial force vectors

DIRECTION OF ACCELERATION	INERTIAL-FORCE TERMINOLOGY Vernacular	Descriptive	Standard
Headward	Eyeballs down	Positive G	$+G_z$
Footward	Eyeballs up	Negative G	$-G_z$
Forward	Eyeballs in	Transverse supine G	$+G_x$
Backward	Eyeballs out	Transverse prone G	$-G_x$
To right	Eyeballs left	Left lateral G	$+G_y$
To left	Eyeballs right	Right lateral G	$-G_y$

Two further terms need to be defined in physical terms before considering the physiological effects of acceleration on man. These are the hydrostatic pressure gradient and the level of hydrostatic indifference. An open column of fluid will exert a pressure at its base equal to the product of its height, the fluid density and the gravitational acceleration. For blood (density = 1.05) this pressure is equal to 0.73 mmHg (97 Pa*) per centimetre of height, or 22 mmHg (2.9 kPa) for the average vertical distance between heart and eye of a normally seated man. In the body, these fluid columns are enclosed and the pressure at any point will be the sum of static and dynamic pressures together with the hydrostatic pressure difference. Thus, for a seated man at 1G, the mean arterial pressure would fall to zero at a virtual level about one metre above the head, while venous pressure is zero at about the level of the mitral valve in the heart. Being caused by the weight of the blood, hydrostatic pressure gradients are increased in proportion to applied acceleration (in an appropriate vector direction), so that $+G_z$ acceleration leads to an inevitable decrease in pressures with distance up the body and to an increase in pressures with distance down the body (Fig. 2-3). At some particular level there must, therefore, be a horizontal plane at which pressures remain constant, independent of the applied acceleration. This is termed the level, or plane, of hydrostatic indifference. Actual levels differ for arteries, veins and cerebrospinal fluid, as they depend upon a multitude of factors such as container rigidity, the presence of valves, transmural pressures, and the action of the heart.

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* (One Pascal is a pressure of one newton per square metre and, hence, a rather small unit. Kilo Pascals (kPa) are commonly used, but it is worth remembering that one deca Pascal (dPa) is, to all intents and purposes, equal to one centimetre of water).

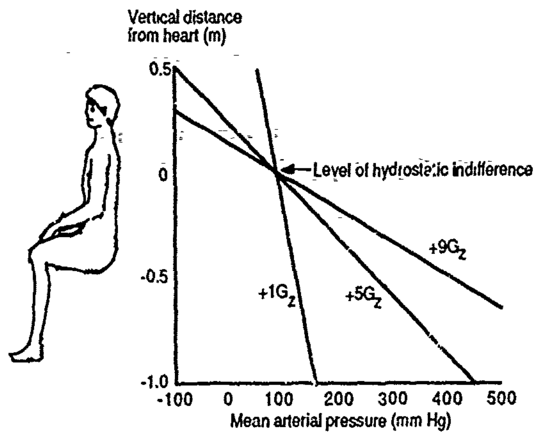


Fig. 2-3

Vertical gradients in hydrostatic pressure down the arterial system of a seated subject for differing +Gz accelerations, assuming constant pressure at heart level.

Finally, the all important role of duration of exposure to acceleration needs to be mentioned. While the physical principles outlined above occur instantaneously, inertial responses such as fluid shifts may take several seconds to develop and physiological responses even longer. Brief excursions may, therefore, be made to high levels of acceleration which could be fatal if prolonged. This is the reason for the accepted division of accelerations into impact forces in which tolerance is determined by the mechanical strength of the body, and sustained accelerations where tolerance is determined by man's ability to remain conscious despite a failing supply of blood to the brain. This distinction has recently become blurred by the extreme agility of modern combat aircraft in which rates of change of acceleration (termed jolt in impact terminology) of 10-15 Gs^{-1} may be achieved. This is a relatively unexplored area due to the inadequate performance of most existing man-carrying centrifuges, but must attain importance in the near future.

Effect of +Gz acceleration on the cardiovascular system (CVS)

The critical role of duration and rate of onset of +G_z exposure has already been alluded to and, therefore, the effects of +G_z on the CVS will be considered temporally.

a. Instantaneous effects. The hydrostatic pressure changes referred to earlier occur instantaneously, so that there will be an immediate and inevitable fall in blood pressure at the level of the eye, brain and carotid baroreceptors. The level of hydrostatic indifference in the arterial system has been variously stated to lie at 'heart level'; at the level of the 3rd rib or 3rd intercostal space; or at the level of the manubrium sterni. Of these, the 3rd intercostal space (133) offers the most logical site as the aortic valve lies at this level and it is reasonable to assume that pressures generated by the left ventricle will be unaffected until secondary changes in venous return have taken place. Burns (35) has measured the aortic valve to eye vertical distance and if one takes an average value of 300 mm, blood pressure at eye level will fall at a rate of 22 mmHg/G, and a mean pressure of zero would be expected at around +4 G_z and a systolic pressure of zero at around +5.5 G_z.

While hydrostatic pressures will increase in parts of the body below the level of hydrostatic indifference (especially so in the dependent lower limbs), actual rises will be somewhat delayed as the compliance (distensibility) of the vasculature will lead to an increase in capacity with increasing pressure, and to an inflow of blood before the theoretical values can be achieved.

b. 1-5 seconds. The passive dilatation of blood vessels below the level of the heart has two consequences for blood pressure. First, dilatation of arterioles reduces their resistance to flow: thus, total peripheral resistance falls and blood pressure (related to resistance by the temporarily unchanged flow) decreases. Second, vascular dilatation, especially of the larger veins, increases their capacity and, transiently, venous return falls to a value less than cardiac output as these vessels fill. Cardiac output then falls to match the reduced venous return and there will be a further reduction in blood pressure at heart level. A similar increase in capacity and reduction in flow resistance is seen in the pulmonary vasculature in dependent parts of the lung.

c. 5-10 seconds. A fall in pressure at head level (hydrostatic changes superimposed upon heart level blood pressure changes) is sensed by receptors located at the bifurcation of the carotid artery in the neck - the baroreceptors of the carotid sinus. This leads reflexly to an inhibition of vagal (parasympathetic) tone and to a stimulation of the sympathetic nervous system, both mechanisms then acting to increase the strength and rate of contraction of the heart, and to increase the resistance to flow of the circulation by provoking a generalised vasoconstriction. These compensatory reflexes take several seconds to develop and the maximum heart rate is only achieved some 15s after the onset of acceleration exposure. Consequently, for a rapid onset of +G_z acceleration, the lowest blood pressure is seen 7-8s into the run and a subsequent recovery in pressure leads to a 1 G or so increase in tolerance for slow onset rate acceleration exposures.

Other baroreceptors in the aortic arch will reinforce the reflex response to a fall in cardiac output and pressure at heart level, but will fail to detect the more cephalad hydrostatic pressure changes and will tend to counter the hypertension needed at heart level for adequate perfusion of the brain. This situation is unique to the high-G environment which in most other respects is comparable to haemorrhage in the responses it evokes. It is also important to note that the baroreceptors are stretch receptors and respond to changing transmural pressure. Hence, an increase in intrathoracic airways pressure will act externally on the aortic receptors which will 'sense' a decrease in aortic pressure. Similarly, pressure applied to the neck overlying the carotid baroreceptors leads to a reflex rise in blood pressure (as the transmural pressure difference has been decreased).

A generalised vasoconstriction acts counter to the needs of some critical tissues. For example, the heart must be adequately perfused if it is to continue to support life, as must the brain stem. Studies of regional blood flow have shown that what actually occurs during acceleration stress is a compromise in which the blood supply to the less essential organs (in terms of immediate survival) falls to very low levels (for example, muscle, gut, liver and kidney), while that to the heart and brain is maintained at close to normal values through local control mechanisms (90).

d. Long term. Compensatory increases in blood pressure lead to a relative hypertension at heart level (maintenance of retinal blood flow at +9 G_z requires a mean pressure in the aorta of some 225 mmHg), and to a further increase in vascular pressures in dependent parts of the body. Further pooling (loss of circulating blood volume to distended vasculature) will occur and, due to the grossly inflated capillary pressures, fluid is forced through the capillary walls into the tissue spaces. This transudation of fluid leads to haemoconcentration and to a further and progressive fall in circulating blood volume until finally, as in haemorrhage, the compensatory mechanisms described above break down with a dramatic slowing of the heart, generalised vasodilation and vaso-vagal syncope. The trigger for this failure in compensation is unknown, but is probably similar to that seen during exposure to lower body negative pressure (a comparable cardiovascular stress), for which cerebral oxygen insufficiency has been postulated (101).

Longer term changes also take place in the body's hormonal responses with the release of several vasoactive agents which will tend to increase blood pressure and so raise G tolerance. Blood levels of the catecholamines, adrenaline and noradrenaline, are increased, due both to direct stimulation of the adrenal medulla and to leakage from sympathetic synapses, while hypotension and hypovolaemia afford a possible trigger for the observed increase in arginine vasopressin (AVP, otherwise known as anti-diuretic hormone, or ADH) and cortisol (151). Though probably inoperative in the acute response to +G_z acceleration, these agents may increase tolerance to more prolonged runs, or to repeated exposures.

The retinal circulation

The retina is perfused from within the eyeball so that its vasculature is exposed to the intraocular pressure of some 15-20 mmHg (2-2.7 kPa). Retinal blood flow will, therefore, cease when the systolic pressure at eye level falls to 20 mmHg or so. Direct measurement of pressures at eye level and observation of the retinal vessels by fundoscopy confirm that this is the mechanism for the visual symptoms seen during exposure to +G_z acceleration, and explains why complete blackout can occur without loss of consciousness. Greyout, or loss of peripheral vision, occurs when systolic arterial pressure at eye level falls to some 50 mmHg and progresses to complete failure of visual function, or blackout, as the pressure falls to around 20 mmHg. Blackout still takes some five seconds to develop, even following the abrupt cessation of retinal blood flow, due to the presence of oxygen reserves in trapped blood and in the retinal tissues.

Being a peripheral phenomenon, the G tolerance as assessed from visual symptoms can be affected by altering the pressure over the eyes. Thus, the application of positive pressure using close fitting goggles reduces tolerance (130), while suction using a similar system, or a complete helmet (97) increases tolerance. As these effects are solely mediated through the eye, however, they have no effect on the maintenance of consciousness during exposure to +G_z acceleration.

The cerebral circulation

In hypotension induced by haemorrhage, consciousness becomes disturbed when the mean arterial pressure at head level falls to around 50 mmHg. During exposure the +G_z acceleration, however, consciousness is well maintained even during blackout when this pressure may fall to 20 mmHg, or less. The reason for this discrepancy appears to lie in the behaviour of the venous drainage from the brain, which acts to some extent like a siphon. Thus, Henry and co-workers (108) showed that, despite collapse of the superficial veins in the neck, the pressure in the jugular vein at its exit from the skull fell significantly below atmospheric pressure during exposure to +4.5 G_z (Figure 2-4). In this way, an arterio-venous pressure differential is maintained, and cerebral blood flow thereby facilitated at lower than expected levels of head-level arterial pressure. The venous siphon is not 100% effective, however, and unconsciousness results when the arterial pressure at head level falls to, and is maintained, around zero mmHg.

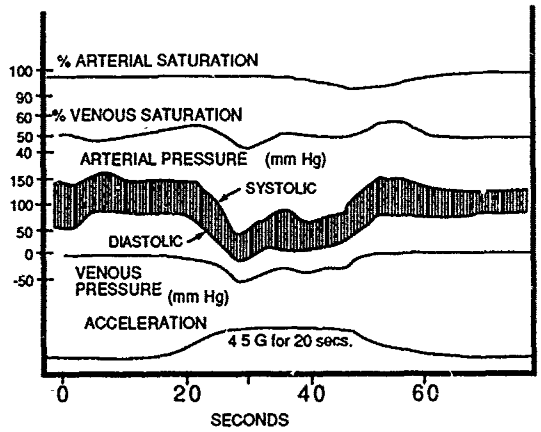


Fig.2-4

The demonstration of a subatmospheric pressure in the jugular bulb of a subject exposed to +4.5 Gz which maintains an effective, though decreased, arterio-venous pressure differential and cerebral blood flow - the so called jugular siphon (From Ref 108).

As with the eye, the brain contains sufficient oxygen reserves to function for several seconds in the absence of blood flow. Using a cervical cuff to occlude blood flow to the brain, Rossen et al (164) showed that the eyes became fixated after 5-5.5s and collapse followed a second later. The unconsciousness produced by rapid-onset G exposure may occur marginally faster, in 4-5s, but any difference is explained by the fact that arterial occlusion traps blood in the brain and provides an extra store of oxygen in the form of oxyhaemoglobin while, with exposure to +G_z acceleration, a considerable volume of blood drains rapidly from the cerebral tissues (96).

Cerebral capillaries are exposed to the tissue pressure within the brain which is itself determined by the pressure of the cerebrospinal fluid. If this pressure were unaffected by $+G_z$, the transmural pressure of the capillaries would fall to zero and the vessels would collapse, with cessation of blood flow independent of any reduction in venous pressure. No measurement of cerebrospinal fluid pressure has been made in man during exposure to $+G_z$ acceleration, but it may be presumed that the column of fluid which extends down the spine leads to a hydrostatic reduction in pressure at head level of sufficient magnitude to maintain capillary patency.

Effect of acceleration onset rate.

It has been shown above that the cardiovascular system's response to $+G_z$ acceleration is multiphasic and takes many seconds to become fully developed. It follows that, for a given plateau level of acceleration, the response, and consequently the tolerance level, will be sensitive to the rate at which that plateau is achieved. This characteristic is illustrated in figure 2-5 in which the $+G_z$ acceleration is plotted against time, and tolerance bands (for the visual symptoms of greyout or blackout, and for loss of consciousness) are indicated for a theoretically infinite number of G-onset rates.

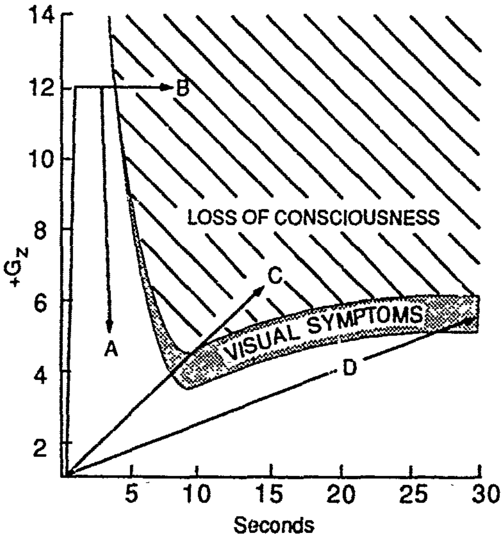


Fig. 2-5

The effect of differing acceleration onset rates on the development of visual symptoms and/or loss of consciousness. Refer to text for details.

When the G-onset rate is so slow that cardiovascular compensation can keep pace with the developing stress (arrow D), tolerance is some 1 G greater when measured by either criterion, than for the more rapid onset shown by arrow C. In each case there will be a significant time interval during which visual symptoms will be present prior to loss of consciousness, and this visual warning should be adequate to allow a pilot to ease off the G or to instigate an effective anti-G straining maneuver (see chapter 3). Non-pilot aircrew would, of course, only have the second option at their disposal.

It may also be seen from figure 2-5 that a very brief incursion can be made to a high level of acceleration (for example, arrow A) without symptoms of impaired blood flow becoming manifest. This can occur, despite cessation of both retinal and cerebral blood flow, since the energy stores of these organs are adequate to maintain function for several seconds. Clearly, for such an incursion to be made, rapid onsets and offsets of acceleration are required. Should such a rapid onset-rate, high-G incursion be maintained beyond this critical time period (as indicated by arrow B), oxygen stores will become exhausted and unconsciousness will ensue without any warning symptoms of visual impairment. This is the specific high risk area in which G induced loss of consciousness (G-LOC) most often occurs (see chapter 5).

Effect of +Gz acceleration on lung function

The influences of $+G_z$ acceleration on lung mechanics and respiratory gas exchange are covered in detail in reference 91. Lung and chest wall mechanics are influenced by the weight of thoracic and abdominal tissue components, and by the vector direction in which the weights act. By increasing the weight of these components, $+G_z$ acceleration acts to exaggerate the changes seen when adopting the upright posture. The increased weight of the chest wall tends to decrease vital capacity and tidal volume, while that of the abdominal contents tends to lower the diaphragm and so to increase functional residual capacity. The inflation of an anti-G suit, however, reverses this latter effect by increasing intra-abdominal pressure so that all lung volumes - vital capacity, tidal volume and functional residual capacity - are decreased. The reduction in tidal volume is compensated for by an increase in the frequency of respiration, and the minute volume is usually increased, at least at lower G levels. These changes are indicated diagrammatically in figure 2-6.

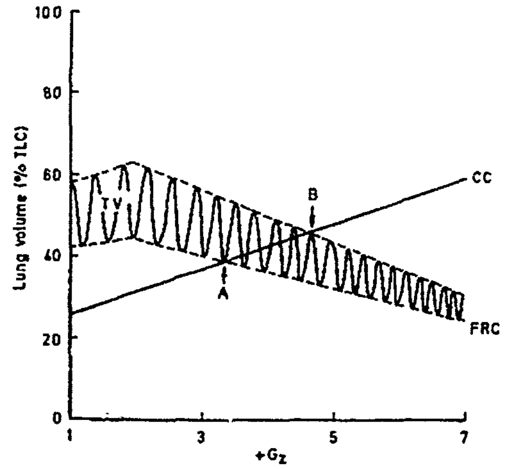


Fig. 2-6

The effect of +Gz acceleration on tidal volume (TV) and functional residual capacity (FRC). Note that closing capacity (CC) becomes equal to FRC at point A and that from point B, basal airways remain closed throughout the respiratory cycle.

Reclining the body posture from seated upright towards supine - i.e. changing the G-vector from $+G_z$ towards $+G_x$ - increases the effect of chest wall weight and reverses that of the abdominal viscera, with all lung volumes tending to be markedly reduced, particularly the functional residual capacity. As we shall see, it is the sensitivity of this latter volume to the acceleration vector which has the greatest influence on gas exchange.

Within the thorax, acceleration increases the disparity in weight between the lung tissue and its contained gas, and the normal gravitational gradient in transpleural pressure is also increased in proportion to the applied G level. At +5 G_z, for example, this gradient, which is due to the weight of the lung tissue, increases from its normal 0.2 cm water/cm to 1.0 cm water/cm and there will then be a 30 cm water (295 Pa) difference in the pressure tending to expand the lung between its apex and its base. In this way an apical alveolus can be fully expanded at the same time that a basal alveolus is at its minimal volume - i.e., the gradient in transpleural pressure produces a gradient in alveolar volume. The regional ventilation which then results from taking in a breath will be small for the distended apical alveoli; will increase down the lung as the less inflated alveoli are more compliant; but will then fall to zero in the dependent lung where intrapleural pressure remains positive.

The hydrostatic gradient in pulmonary vascular pressures which determines the regional distribution of pulmonary arterial blood flow is also increased by acceleration, so that the lung apex becomes unperfused and the base overperfused. Though efficient gas exchange can still take place at intermediate levels where lung function remains relatively normal, the particular phenomenon of airway closure which occurs when alveoli attain their minimal volume leads to a right-to-left shunt of venous blood and a decrease in arterial oxygen saturation. This situation needs to be considered in further detail as it has relevance to some specific effects of positive pressure breathing, anti-G suit inflation, and the fraction of oxygen in the inspired gas.

Airway closure and acceleration atelectasis

As stated above, an enhanced gradient of transpleural pressure causes a gradient in alveolar size such that alveoli in the dependent lung may shrink to their minimal volume. Further shrinkage is prevented, despite an increasingly positive intrapleural pressure, by closure of small conducting airways, the terminal bronchioles. With normal gravitational acceleration, such closure only occurs as the overall lung volume approaches residual volume, but as the level of acceleration increases, airways close at a correspondingly greater lung volume (116). The overall lung volume at which airway closure can first be detected (using single breath tests or radioisotope techniques) is termed the closing volume of the lung (or closing capacity if measured in absolute terms) and its increase with the G level is also indicated in figure 2-6.

Reference to figure 2-6 shows that, under the influence of gravity (+1 G_z), a subject normally breathes at lung volumes greater than closing volume (functional residual capacity greater than closing capacity). In the absence of anti-G suit inflation this relationship is maintained at higher G levels, but as the suit normally inflates above 2 G and the functional residual capacity decreases, there comes a point (A in figure 2-6) at which airways will close momentarily at the end of each expiration. With a further increase in acceleration, closure moves up the tidal volume until (point B) airways remain closed throughout the respiratory cycle. A deeper inspiration can still open these airways and ventilate dependent alveoli but, as the level of acceleration continues to rise, the increasing volume required becomes harder and finally impossible to achieve.

As long as an alveolus is ventilated at least at some point in the breathing cycle, gas exchange can still occur. However, when the conducting airway remains closed off, gas exchange will cease once equilibrium is attained between the alveolar gas and the capillary (venous) blood. Oxygen will be rapidly absorbed, but the poor diffusibility and solubility of any nitrogen present will act as a brake on a further reduction in alveolar volume. Continued perfusion will, however, constitute a right-to-left shunt and the resulting venous admixture will lead to a fall in the oxygen saturation of systemic arterial blood. With return to a lower G level, the terminal bronchioles will reopen and normal ventilation and gas exchange will be resumed. When 100% oxygen has been breathed, however, absorption of the trapped gas will continue until all non-ventilated alveoli have been rendered gas free (absorptional collapse or atelectasis), a process which takes as little as 15s depending upon the regional blood flow and atmospheric pressure. Once this process has occurred, the normal levels of transpulmonary pressure which follow return to 1 G conditions are insufficient to overcome surface tension forces within the small airways, and the collapse persists. This leads to retrosternal discomfort, difficulty in taking a deep breath and a tendency to cough (the symptoms of acceleration atelectasis) and to the persistence of shunting and arterial desaturation. Reinflation can take several hours, but may be almost immediate following multiple attempts at a maximal inspiration and the bout of coughing which almost inevitably ensues.

Factors modifying the development of acceleration atelectasis

The action of nitrogen as a brake to the development of absorptional atelectasis has already been mentioned, and as little as 40% in a nitrogen/oxygen mixture is sufficient to reduce symptoms to a low order. Other inert gases will have a comparable effect, and the apparent disadvantage of oxygen concentration systems in that they also concentrate atmospheric argon, may actually be beneficial in this respect (183). Oxygen systems for use in aircraft capable of sustaining +3 G_z or more should not deliver more than 60% oxygen at cabin altitudes of up to 15,000 ft, or 75% from 15,000 ft to 20,000 ft (180).

Figure 2-6 stresses the importance of the relationship between functional residual and closing capacities, and any factor which increases lung volume will also tend to reduce the development of atelectasis. Breathing at a positive pressure for enhanced G tolerance (Pressure Breathing under G, or PBG - see chapter 4) will also increase the expiratory reserve volume (98), while the addition of chest counterpressure (Assisted, or Balanced PBG) will tend to negate this effect. PBG does produce a reduction in symptoms and signs of acceleration atelectasis (183); and surprisingly, chest counterpressure does not appear to be contra-indicated: other factors - a greater voluntary depth of inspiration, for example - may be involved.

Effect of Positive Intrathoracic Pressure Breathing

The easiest way to increase intrathoracic pressure is to make a forceful expiratory effort against a closed glottis - the so called Valsalva maneuver, whilst intra-abdominal pressure can be increased by straining the abdominal musculature, so maintaining a normal pressure differential across the diaphragm. An intra-thoracic pressure of up to 110 mmHg can be sustained for a few seconds and, as would be expected, this has a profound effect on the systemic circulation. The increase in airway pressure is instantly transmitted to the blood within the thorax and abdomen (great veins, atria, pulmonary circulation, ventricles and aorta) and subsequently to the peripheral arteries on an almost one for one basis. This increase will tend to be supported reflexly, as the aortic baroreceptors will interpret an increase in intrathoracic pressure as a fall in aortic blood pressure. However, the great distensibility and capacity of the peripheral veins precludes an equivalent rise in venous pressure, venous return fails and there is a pronounced shift in blood volume from the central reservoir to the periphery. Consequently, cardiac output falls so that, if the maneuver is extended, there is a narrowing of the arterial pulse pressure, a falling mean pressure and, ultimately, syncope.

Intrathoracic and intra-abdominal pressures are transmitted to the cerebrospinal fluid through the intervertebral foramina so that transmural pressures within the cerebral vasculature remain relatively normal and the intracranial capillaries are protected.

Relaxation of the Valsalva maneuver is followed by an overshoot in blood pressure due to a sudden increase in venous return as the flood gates are opened, together with continued sympathetic activity engendered by the previously falling arterial pressure as sensed by the carotid (and aortic) baroreceptors.

Breathing at a positive pressure of up to 70 mmHg (9.3 kPa) has become a standard emergency procedure for increasing the inspired oxygen tension at altitude. The physiology of pressure breathing has been studied in detail by Ernsting (77) and is essentially similar to that of the Valsalva maneuver except that respiration is continued and the procedure can be considerably prolonged - minutes rather than seconds. The systemic effects, and the degree of enhancement of the systemic arterial pressure, depend to a considerable extent on the degree of counterpressure applied externally to the body. With no counterpressure (unassisted, or unbalanced, positive pressure breathing) the arterial pressure rises by about half the applied breathing pressure, while with the application of counterpressure to the trunk by means of an inflated jerkin, it rises by up to 100%. Further assistance from the added inflation of an anti-G suit causes the arterial pressure to rise by 100% to 125% of the applied breathing pressure (77). Similarly, the incidence of pressure breathing syncope is reduced by the extended coverage of counterpressure garments, and the level of breathing pressure at which it may occur is also greater.

The Valsalva maneuver and positive pressure breathing (either assisted or unassisted) form the basis of two effective countermeasures to the systemic effects of sustained $+G_z$ acceleration - the anti-G straining maneuver and pressure breathing during G - which will be considered in detail in chapters 3 and 4 respectively.

Musculo-Skeletal Effect of +Gz

The increased weight of the soft tissues and limbs produces significant decrements in mobility even at low levels of $+G_z$ acceleration. It becomes impossible to rise from the sitting position at about $+3\ G_z$ and the movement of unsupported limbs becomes progressively more difficult with upwards motion impossible at between $+6\ G_z$ and $+8\ G_z$. With support of the forearm and hand, however, fine control movements of the fingers can be made at $+10\ G_z$ or more provided that consciousness is maintained. Even without heavy headgear, a subject cannot raise his head, once lowered, at above +7 or $+8\ G_z$, and at even lower levels movement becomes jerky and poorly coordinated. At high levels of sustained $+G_z$, there is a potential risk of intervertebral disk rupture and also of soft tissue injury to the neck if the head is allowed to fall. Neck strengthening exercises are recommended for pilots flying the more agile aircraft types (see Chapter 7).

The effort involved in performing an effective anti-G straining maneuver (see Chapter 3) is extremely tiring, and the duration of tolerable G exposure may be limited by fatigue rather than by failure of cerebral perfusion. Blood lactate levels measured following centrifugation or air combat show significant increases, and demonstrate that anaerobic metabolism is the primary basis for the energy requirement, an observation supported by the finding that resistance (weight) training increases the time for which a simulated air combat maneuver (SACM) can be tolerated, while aerobic training does not (75 and see also Chapter 7). During high $+G_z$, muscle blood flow will be reduced in an attempt to divert the reduced cardiac output to the brain and myocardium, in addition to the direct effect of isometric muscle contraction on local blood flow. However, while maximum blood lactate levels appear to correlate well with SACM tolerance times (186) and with peak heart rates (53), they have not to date served as a useful measure of the effectiveness of PBG versus the AGSM, despite the subjectively lesser fatigue engendered by the former procedure.

FURTHER READING

Further details of the physiological effects of $+G_z$ acceleration may be found in a number of text books and review articles of which the following are both accessible and recommended. Whilst fairly aged, the first of these contains the most comprehensive account of the classical acceleration references.

A Textbook of Aviation Physiology. Ed. J.A. Gillies. Pergamon Press, London. 1965.

Man at High Sustained $+G_z$ Acceleration : A Review. R.R.Burton, S.D.Leverett and E.D.Michaelson. Aerospace Med. 45: 1115-1136, 1974.

Fundamentals of Aerospace Medicine. Ed. R.L.Dehart. Lea and Febiger, Philadelphia. 1985.

Aviation Medicine. Second Edition. Ed. J. Ernsting and P. King. Butterworths, London. 1988.

SUMMARY

Chapter 2, Physics and Physiology, starts by describing the basic Newtonian mechanics of centripetal acceleration and the resulting inertial centrifugal force. The unit G is defined and the inertial force terminology given for its six vector directions ($\pm G_{X,Y,Z}$). Hydrostatic pressure gradients and the effect of G are considered in particular relation to the heart-brain axis, and the concept of a plane of hydrostatic indifference is outlined with reference to the arterial, venous and cerebrospinal fluid systems. The effect of $+G_z$ acceleration on the cardiovascular system is considered in detail in relation to the rate of G onset and duration of G exposure, and to the physio-logical responses evoked through the baroreceptor reflexes. Fluid shifts, decompensation and vaso-vagal syncope are described together with hormonal responses to sustained $+G_z$. The particular characteristics of the retinal and cerebral circulations, and the effects of $+G_z$ induced inadequacies of blood flow, are considered in relation to visual symptoms of greyout and blackout, and to G-induced loss of consciousness (G-LOC). The effect of $+G_z$ acceleration on lung function is described together with the mechanisms responsible for the resulting ventilation/perfusion inequalities, airway closure, absorptional lung collapse (acceleration atelectasis) and arterial oxygen desaturation. The effects of positive pressure breathing are discussed in relation to the Valsalva maneuver, the anti-G straining maneuver (AGSM), and G protection (PBG) with and without the use of counterpressure. Finally, some effects of $+G_z$ acceleration on the musculo-skeletal system are considered with specific reference to the energetics of the AGSM, blood lactate levels and fatigue.

BASES PHYSIQUES ET PHYSIOLOGIQUES.

Ce chapitre débute par la description des bases de la mécanique newtonienne concernant l'accélération centripète et la force d'inertie qui en résulte. La force inertielle et ses six vecteurs d'application ± G_X, G_Y, G_Z sont ensuite définis. Les gradients de pression hydrostatique et les effets de l'accélération sont présentés. Le niveau d'équilibre de pression hydrostatique est défini en fonction des systèmes artériels, veineux et du fluide cérébro-spinal. Les effets des accélérations $+G_Z$ sur le système cardio-vasculaire sont étudiés de façon fine en fonction de la vitesse de mise en accélération et de la durée de cette accélération. Les réponses physiologiques sont présentées en fonction du baroréflexe. Les déplacements du volume sanguin, la décompensation et la syncope vaso-vagale sont décrits avec les réponses hormonales aux accélérations $+G_Z$ soutenues. Les voiles gris et noir et les pertes de connaissance (G-LOC) sont expliqués par l'insuffisance du débit sanguin des circulations spécifiques rétinienne et cérébrale. Les effets des accélérations $+G_Z$ sur la fonction pulmonaire sont décrits par les inégalités du rapport ventilation-perfusion, le collapsus pulmonaire (entraînant des atélectasies) et la désaturation du sang artériel. Les effets de l'augmentation de la pression intrathoracique sont discutés en fonction de la manoeuvre de Valsalva, de la manoeuvre anti-G (manoeuvre de contraction musculaire et de respiration pour protection anti-G, en anglais anti-G straining manoeuvre ou AGSM) et de la respiration en pression positive (Positive Pressure during G ou PBG). Enfin, certains effets des accélérations $+G_Z$ sur les systèmes musculaires squelettiques sont examinés en fonction de l'énergie dépensée (lors de la manoeuvre anti-G) et des niveaux de lactatémie et de fatigue.

CHAPTER 3
G TOLERANCE AND STANDARD G-PROTECTION METHODS

ACCELERATION TOLERANCE

Pilots of high performance aircraft must tolerate G forces (>5 G) for considerable periods of time if they are to be successful in combat. Tolerance measurements of this high G environment must, therefore, include as major parameters, both G level and the time spent (duration) at G.

Tolerance criteria for G-level usually involve the ability of a subject to maintain vision (loss of which is called blackout) or consciousness. Performance measurements, although probably the most appropriate criteria for operational concerns, are only sparingly used to quantify G-level tolerance. No tests that adequately measure performance during these short-duration G exposures, as it would pertain to flying a high performance aircraft, are available.

For G duration, the usual tolerance criterion is a subjective fatigue end point that can be validated with the blood level of lactate.

G-Level Tolerance

The inability to tolerate G acceleration level is the result of insufficient blood flow to the head. This condition has been the basis for various objective and subjective criteria of G-level tolerance. Objective evaluation of cerebral circulatory function is generally provided by the invasive measurement of direct arterial blood pressure (Pa) at the level of the eye (123,134), noninvasive measurement of blood flow in the temporal artery by Doppler techniques (123,129,167), and ear lobe opacity using photometric systems (219). More recently, the transcranial Doppler has been used to measure cerebral arterial blood flow directly in the human while cerebral blood content and oxygen status have been measured using multiwavelength near infrared spectrophotoscopy (94,197). Classically, however, the index of circulatory function in the head has been subjective, involving the recognition of differing levels of visual deficiency (grayout or blackout). The physiologic basis of light loss during exposure to G is discussed in Chapter 2.

These levels of light loss during G exposures on a centrifuge are measured using many different techniques. A simple method routinely used at several laboratories utilizes a straight light bar placed 76 cm in front of the subject at eye level in the gondola of the centrifuge (Fig. 3-1). This straight light bar is 71 cm long with a small green light (2.5 cm diameter) at each end. The center of this light bar has a 2.5 cm diameter red light. The red light luminance is 500 candela/m^2, and the green light has twice that luminance. These dimensions are in compliance with NATO Stanag 3827 (179). The level of G where the green peripheral lights can no longer be seen by the subject is the peripheral light loss (PLL) G tolerance (100% PLL). At higher G levels, the central red light becomes less intense and the level at which its brightness is subjectively judged to have fallen to half is considered to be 50% central light loss (or 50% CLL) threshold. This level of light loss is the maximum light-loss level usually used in the laboratory. The G level where 50% CLL occurs is considered the "blackout" tolerance. Complete CLL or absolute blackout is not generally attempted because of G-LOC concerns.

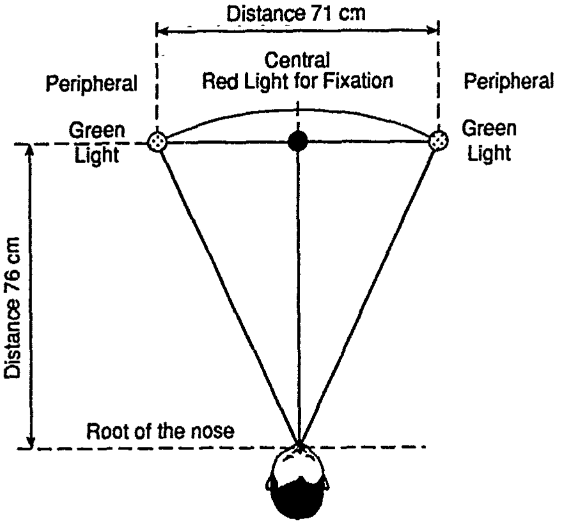


Fig. 3-1
Light bar viewed by subject during centrifuge runs. The green and red lights are 2.5 cm in diameter.

The classic G-level tolerance is determined on subjects that are "relaxed" and is considered an individual's basic G tolerance. This relaxed tolerance measures the cardiovascular response to an increased G exposure. Although relatively high relaxed G tolerances are not required to tolerate high levels of G, extremely low relaxed G tolerances are considered important enough for developing pilot selection standards that excludes pilots with low G tolerances.

In determining relaxed G-level tolerances in the laboratory, the relaxed seated subject, not using an inflated anti-G suit, looks straight ahead at a light bar (Fig. 3-1) as 15 sec epochs of increasing higher G levels are provided by the centrifuge at defined (1 to 6 G/sec) onset rates with intervening 30 sec to 1 min rest periods. The initial G-level is usually 3 G with succeeding G-level increases of 0.2 to 0.5 G each. Because the subject is relaxed and the onset of G is rapid at 1 G/sec, this G tolerance is called a relaxed rapid onset rate (ROR) tolerance.

A slower G-onset rate is also used in the laboratory at 0.1 G/sec onset or sometimes 1 G/15 sec with a single ramp exposure (not several epochs like ROR testing) that is terminated by the relaxed subject as the desired light loss level is reached. The G level attained at this point is called the relaxed gradual onset rate (GOR) tolerance. This slower-G onset test allows time for the subject's baroceptor response to develop so that the G or tolerance is higher than the ROR tolerance by approximately 1 G. Hence, the baroceptor response of an individual from the G stimulus can be measured by the difference in the relaxed GOR and ROR tolerances.

G-onset rates faster than 1 G/sec (e.g., 6 G/sec) result in a relaxed G tolerance approximately 0.3 G lower than the ROR tolerance thereby defining another relaxed G-level tolerance called very rapid onset rate (VROR) (38). However, because of the existence of a 4-5 sec latent (symptom-free) period at the beginning of a G exposure with an extremely rapid G onset (e.g., 10 G/sec onset), a "relaxed" person can attain very high G levels (e.g., 14 G) without exhibiting any symptoms of loss of G-level tolerance if they immediately return to 1 G (20). This latent period is based on the energy (neurotransmission) reserve capacity of the individual's eyes and brain. This latent symptom-free period, however, can be hazardous to pilots if during a very rapid G onset rate maneuver they exceed their G-level tolerance and remain there, beyond this latent period, then G-LOC can occur without any preceding light-loss symptoms (see Chapter 2, Fig. 2-5).

Various attempts have been made to quantify more accurately these subjective light-loss criteria during G exposure. One of the more commonly used methods is the curved light bar. One version, called the high-resolution visual field limit tracker, is used in measuring visual fields of subjects near their G-tolerance PLL limits (87). This apparatus consists of an array of 120 white lamps located 1 deg apart on a 120 deg curved horizontal bar situated 76 cm in front of the subject's eyes. Using a controllable reversible response switch, the subject is able to track changes in peripheral vision. A subject using the device, and a recording showing the visual response to a GOR run until grayout has occurred, are shown in Figure 3-2.

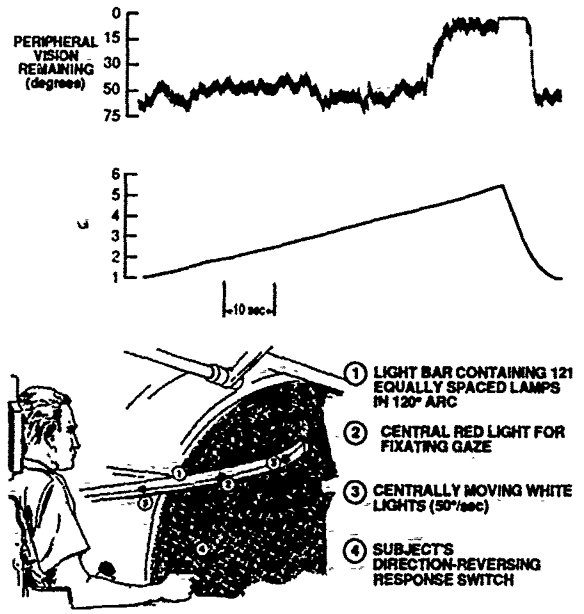


Fig. 3-2

Subject operating the high-resolution visual field limit tracker in the horizontal mode. Response to visual field reduction during GOR to 5.5 G is shown above (87).

G-induced loss of consciousness (G-LOC) occurs in pilots flying high performance aircraft even while using all of the customary G-protection methods. Therefore, the use of G-LOC as a tolerance criterion in the laboratory has considerable appeal, making it particularly relevant to flight operations. However, since the extent of possible pathologic sequelae, if any, is not known, deliberate G-LOC is only occasionally used in the laboratory and then to study the human characteristics of its induction and recovery from G-LOC (109,205) (see Chapter 5).

Numerous relaxed G-level tolerance studies have been conducted, but the classic for ROR is that reported by Cochran et al (62) in 1954 on 1,000 subjects with various backgrounds (Table 3-1). A population distribution of several hundred USAF TAC pilots for relaxed GOR tolerances is shown in Figure 3. Assuming the two populations have the same G-level tolerances, the median GOR tolerance for TAC pilots is about 5 G, suggesting a baroceptor response, as expected of about 1 G over the ROR tolerance of 4.1 G shown in Table 3-1.

Table 3-1

G-Level tolerances of 1000 relaxed subjects not wearing anti-G suits at 1 G/sec onset rate (ROR) (62).

Criterion	Mean threshold (G units)	deviation (G units)	Standard Range (G units)
Grayout and loss of peripheral vision	4.1	± 0.7	2.2 - 7.1
Blackout	4.8	± 0.8	2.7 - 7.8
Unconsciousness	5.4	± 0.9	3.0 - 8.4

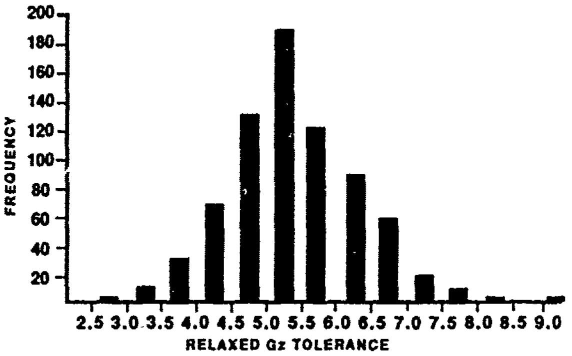


Fig. 3-3

Relaxed GOR G-level tolerance distribution for several hundred TAC pilots receiving high-G centrifuge training at USAFSAM in the F-16-configured seat. The mean tolerance is about 5 G, the standard deviation is almost 1 G, and the range is from less than 3 to more than 7 G (86).

A straining type of G tolerance determination to measure the capability of a subject to increase (in units of G) their relaxed G-level tolerance. This tolerance measurement begins with a relaxed GOR determination, but instead of stopping the centrifuge at the G tolerance light-loss level, the subject begins to perform an anti-G straining maneuver (AGSM). This maneuver is maintained as the G level continues to increase at 0.1 G/sec until a 9 G limit is reached or the subject once again experiences light loss. The difference between the relaxed GOR tolerance and straining GOR tolerance is considered a reliable measure of that person's ability to perform an AGSM. Various types of AGSM, and their physiologic bases, in increasing G tolerances are discussed later in this chapter.

The maximum G level obtainable using the anti-G suit and AGSM has never been systematically measured in the laboratory. The maximum G level-duration attempted in an upright seat using only an anti-G suit and AGSM was 9 G for 45 sec which was attained by 9 of 14 subjects in a study conducted at USAFSAM in 1972 (157). Higher G levels would have been possible for some of the subjects—perhaps up to 10 or 11 G for a few subjects with extremely high G tolerances. Interestingly, as shown in Figure 3-4, a high relaxed G-level tolerance is not necessary for tolerating high G levels when the customary anti-G suit and AGSM are used; i.e., the correlation of determination of 0.16 (r^2 of Fig. 3-4) indicates that only 16% of the high-G straining tolerance is dependent upon a person's relaxed ROR tolerance (47).

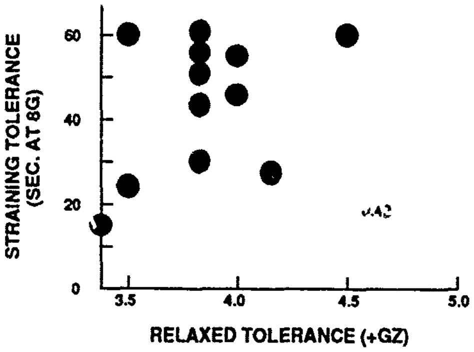


Fig. 3-4

Statistical correlation (correlation coefficient, r = 0.42; and correlation of determination, r2 = 0.16) between relaxed G tolerances and straining tolerances (s) at 8 G for a maximum of 60 sec in the same subjects (47).

G-Duration Tolerance

Modern fighter aircraft are capable of sustaining extremely high G for several minutes (e.g., F-16 is capable of sustaining 9 G in level flight while the fuel lasts), and most pilots can tolerate these levels of G using standard G-protective methods. However, once a G-level is achieved, then G duration becomes the primary determinant of tolerance. This criterion of G tolerance has operational relevance since incidents of G-LOC involving high performance aircraft occur after the pilot has been in an aerial combat maneuver for some time suggesting that fatigue is an important factor.

Of particular interest is the different G duration-level relationship from 3 to 5 G compared with 6 to 9 G—the former representing relaxed G tolerance and the latter, of course, tolerances where the anti-G suit and AGSM must be used. These different slopes indicate that the limiting factors at the lower G level are not limiting at higher G levels. It is also interesting that the use of an anti-G suit up to levels of 5 G didn't increase the duration tolerance. Of course, at 6 G and above, the anti-G suit is required.

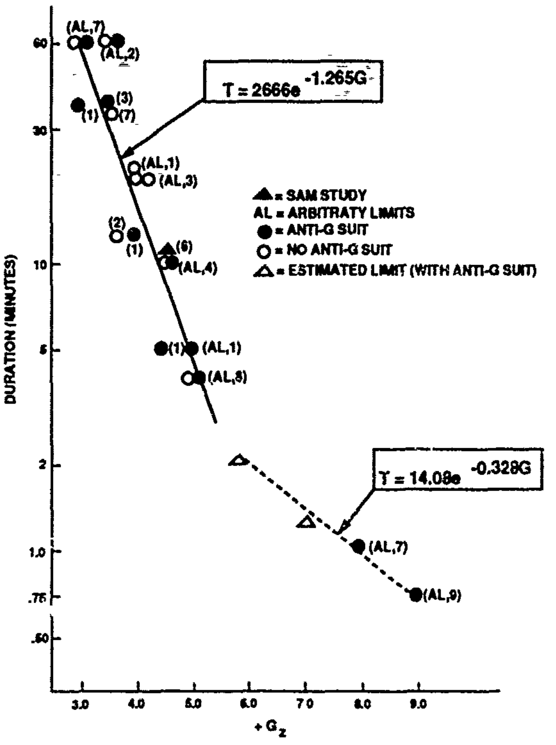


Fig. 3-5

Tolerance times (min) at different G levels using subject fatigue as the endpoint (40,150). Number of subjects per tolerance endpoint is in parentheses.

Fatigue-based duration tolerances involving higher G levels are most commonly measured using a G profile called a simulated aerial combat maneuver (SACM). This profile uses fatigue (as subjectivity determined by the subject) as the tolerance endpoint. The most commonly used SACM is a repeating 4.5 G for 15 sec to 7.0 G for 15 sec, until the subject (wearing an anti-G suit) becomes too fatigued to continue or begins to lose the lights (49) (Fig. 3-6).

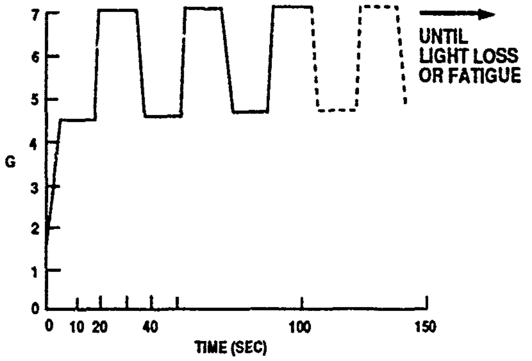


Fig. 3-6

G profile used to measure G-duration tolerance -- simulated aerial combat maneuver (SACM) (49).

Several modifications of this SACM have been developed, but subjective fatigue remains the tolerance endpoint with the blood lactate level as a supporting parameter (186). A relationship between SACM tolerance and relaxed G tolerance has been determined using different back angles. This relationship demonstrates that these differently based tolerances are physiologically coupled (Fig. 3-7).

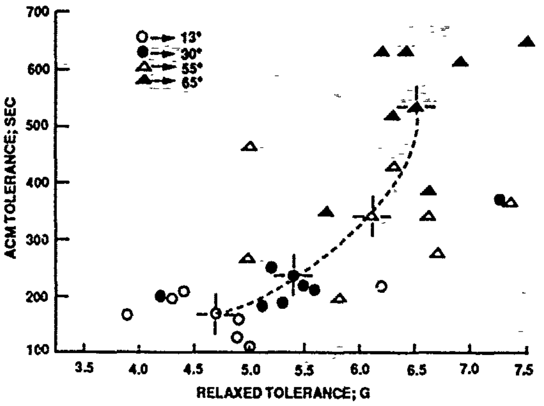


Fig. 3-7

Relationship between GOR relaxed G tolerances and SACM fatigue tolerances at different seat back angles (subjects reclined), thereby reducing their eye-heart vertical distance (49).

Fatigue also plays a significant role in the level of G that a pilot can tolerate. A hypothesis for this relationship has been suggested recently, based on the isometric contraction strength of muscles that provide the basis for the AGSM used to increase G tolerance. It is generally assumed that 100% of a pilot's AGSM capability is required to tolerate 9 G. Since isometric contraction strength decreases at the rate of 1% per second because of fatigue, then a reduction in G-level tolerance of about 1 G (or 25% of the pilot's ability to perform a maximum AGSM) will occur in the first 25 sec of an ACM if a significant portion of the maneuver is very high G (40). The increase in lactate levels is significantly correlated with the duration of the SACM, indicating the importance of anaerobic metabolism in supporting the AGSM (Fig. 3-8).

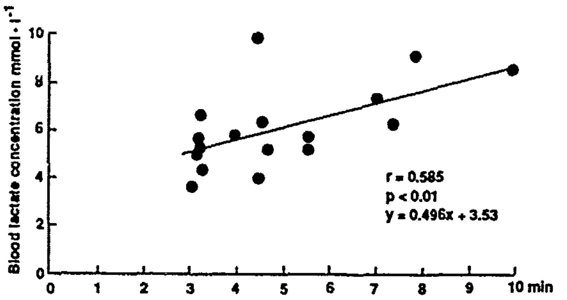


Fig. 3-8

The relationship between ACM time and blood lactate concentration. Each dot represents an individual value. Samples (n = 18) were obtained in student pilots before, in the middle of, and after the training period (186).

Performance Criteria

Practical considerations require that criteria of acceleration tolerance be at a level of physiologic capability where the pilot remains proficient in the performance of their flying duties during an ACM. Simple physical loading, which naturally accompanies acceleration progressively and rapidly, impedes body and limb movement. For instance, raising the entire body against a gravitational field is difficult at 2 G and impossible at 3 G. Donning a parachute at 3 G requires 75 sec—as compared to a normal 17 sec at 1 G. At 6 to 7 G, raising the arms (as required to initiate ejection) becomes extremely difficult.

Even though there are compelling reasons for measuring performance during G exposures, there are problems that have prevented its use as a tolerance criterion in the laboratory. A critical measure of performance, cognition, requires a considerable amount of time to accomplish. But, since high G exposures are generally a minute or less in duration, performance measures are usually limited to tracking (error score) or "shooting" at a target (hit/miss score)—parameters that require only motor skills (47,67). Performance measures of cognition only occur at low G levels where duration of exposure is not restrictive (98).

Therefore, performance measurements are based on motor-types of activities, they tend to degrade rapidly at the higher G levels where physical activity becomes more difficult. This reduction in performance has been estimated by comparing data from 4 different G studies (Fig. 3-9) (47). A performance reduction of 50% occurs at about 6-7 G.

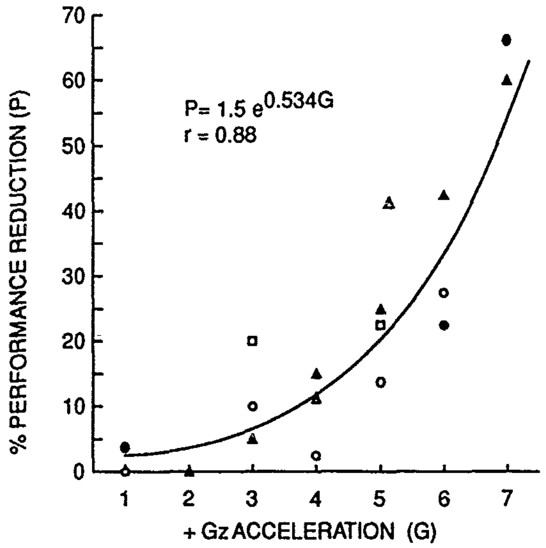


Fig. 3-9

The effect of sustained G on percent reduction in performance comparing several studies. Each study is represented with a different symbol (47).

Biological Factors Affecting G Tolerance

Several biological factors contribute to an individual's acceleration tolerance. These factors can be important in both G-level and duration tolerances. It has been shown that individuals with better high sustained G tolerances have superior responses to 15 different physiologic parameters (36). These parameters involved aerobic and anaerobic metabolism, cardiovascular responsiveness and recovery, levels of fatigue, as well as measures of psychomotor performance. There is an inverse relationship between stature and G-level tolerance (120) that is the result of the heart-eye distance that is inversely correlated with relaxed G-level tolerance. There is a direct correlation between resting systolic arterial blood pressure and relaxed G-level tolerance in men (120,146). Individuals exhibiting the greatest heart rate during treadmill exercise generally have a higher G-level tolerance (198), presumably related to a greater sympathetic response. Gender does not have a significant effect on tolerance when female G tolerance values are adjusted for their smaller body size

(88). Age is directly related to relaxed human G-level tolerance as is body mass (111,182). This age effect is probably related to an increased arterial pressure (198).

Recently, Dr. Per Tesch (personal communication) from the Karolinska Institute, Stockholm, Sweden, has identified four factors that affect G-duration tolerance: inversely related are subject height and % body fat; while directly related are heart volume and muscle fiber size.

Environmental Factors Affecting G Tolerance

Thermal and Dehydration Effects:

Many NATO Air Forces have long been concerned about the effects of high environmental temperatures on G tolerance in pilots since many air bases are located at latitudes where cockpit temperatures can easily climb to 60 deg C.

The effects of hyperthermia on the cardiovascular system are well known. Briefly, hyperthermia causes a peripheral vasodilation that increases the body's blood volume capacity markedly reducing blood flow and vascular resistance that can cause a reduction in resting arterial pressure (Pa). Also, these cardiovascular effects limits the capabilities of the body to respond to other conditions that tend to reduce Pa. Therefore, hyperthermia will reduce both G-level and duration tolerances.

Hyperthermia, especially if the core body temperature is increased—an increase of 1.5 deg C oral temperature going from 37.0 deg C to 38.5 deg C—caused a decrease of approximately 0.9 G. An increase in skin temperature from 32.6 deg to 35.1 deg C, without any change in core temperature, caused only a 0.3 G decrease in tolerance (3,63,144). However, a considerable amount of this loss of G-level tolerance is associated with dehydration. If hydration is maintained in hyperthermic conditions, G tolerance is usually unaffected (184).

Dehydration alone, without thermal changes produced by sodium deprivation, caused a significant reduction in relaxed ROR and GOR tolerances (173). With a reduced sodium intake of only 10 mEq per day for 60 days, plasma volumes were reduced by a mean of 16% that was associated with a reduction in relaxed ROR of 0.5 G, and in relaxed GOR of 0.9 G.

Cold appears to slightly increase relaxed G tolerances. In two studies, subjects had skin temperatures of 30 deg C (3) and 25 deg C—the subjects in the latter study were shivering (144). Only the shivering subjects had an increase in relaxed G tolerance—0.4 G increase while wearing anti-G suits. However, keeping pilots uncomfortable and shivering does not appear to be an acceptable operational method to increase G tolerance.

An increased heat load with dehydration significantly reduces G-duration tolerance. Nunneley and Stribley (156) and Balldin et al (13) found a 40% reduction in SACM tolerance times with 3% dehydration. As with G-level tolerance, G-duration tolerances were restored with rehydration. Therefore, the importance in maintaining hydration of pilots of high performance aircraft in hot climates has clearly been demonstrated. An ambient temperature of 51 deg C significantly increased heart rate and reduced performance components during a 5 G SACM (23).

Inhaled Gas Mixtures:

Relaxed G-level tolerances are essentially a function of Pa; i.e., 25 mmHg Pa is equivalent to 1 G (37). Consequently, the effect on G tolerances of inhaled gas mixtures (i.e., increased or decreased oxygen and/or carbon dioxide tensions), must be considered as the gases affect the cardiovascular system. Since G-duration tolerances are a function of anaerobic capacity, changing the oxygen concentration of inhaled gas mixtures probably does not directly affect G-duration tolerance. Perhaps some indirect effect might occur from changes in local blood flow in skeletal muscles used in the AGSM.

Hypo-Hyperoxia: Gauer (81) and Burgess (30) found a reduction in relaxed G tolerances of about 0.5 G at altitudes of 18,000 ft (81) or while breathing 10% oxygen (30). Breathing 10% oxygen at 1 G reduces Pa by about 10 mmHg that would account for this reduction in tolerance although there is an increase in cerebral blood flow of 35% with hypoxia (118). Interestingly, Gauer reported an increase in G tolerance of 0.1 G at 10,000 ft altitude that he considered real, but could not explain. However, this situation may be explained with hyperventilation (that is probably occurring at this altitude), since it raises Pa by 8 mmHg (118). However, since hyperventilation can lead to cerebral dysfunction, it is not recommended as an operational method to increase relaxed G-level tolerance even temporarily.

Breathing 100% oxygen causes an initial increase in G tolerance of about 0.5 G with an increase of 11 mmHg of Pa that is lost if increased oxygen continues to be breathed (19,26,118). An increased concentration of inhaled oxygen reduces cerebral blood flow by 13% (118). Breathing 100% oxygen did not affect G-level tolerance nor performance up to 9 G with subjects reclined to 55 deg seat back angle even though desaturations that usually occur at G were prevented with high oxygen concentrations (119).

Inhaled oxygen concentrations greater than 60% in combination with increased $+G_z$ and the anti-G suit will cause acceleration atelectasis (see Chapter 2 for details) (117,220).

Hypo-Hypercapnia: Hypercapnia significantly increases relaxed G-level tolerances because of its unique capabilities of increasing both Pa and cerebral blood flow. While breathing 7.6% CO_2, Pa can be increased 30 mmHg (73) plus increasing cerebral blood flow by 75% (118). Higher concentrations up to 10.4% CO_2 caused a slight additional increase in Pa above the 30 mmHg found with 7.6% CO_2 (73). Krutz (123) reported that breathing 5.2 or 7.9% CO_2 increased relaxed $+G_z$ tolerance 0.5 and 0.7 G, respectively. Similar results were reported much earlier by Matthes (145). Increasing the concentration of inhaled CO_2 is considered as an operational method to improve pilot tolerance—see the next chapter (123).

Adaptation to Repeated Acceleration Exposures

Although physiologic adaptation to repeated G exposures has never been systematically studied in humans, there is some evidence that it does occur in the high G environment. Spence et al (178) thought that frequent (weekly) G-exposure was necessary to maintain maximum G tolerance to an SACM. Boutellier et al (22) reported that "only subjects who were regularly exposed to 3 G were able to tolerate a half hour exposure to that acceleration." This training effect appeared to be lost within 2 weeks of nonexposure. Similar ideas are common among fighter pilots, particularly the belief that some G tolerance is lost if there is a significant (unspecified) hiatus in flying time.

Frequently, high G exposures cause cutaneous petechiasis, small pinpoint hemorrhages under the skin ("high-G measles"), especially in the lower part of the body. Their occurrence is less common in pilots frequently flying high-G missions and in centrifuge subjects routinely exposed to high G (200).

Several animal studies (34,51,74) indicate that there is an adaptation which increases G tolerance with frequent acceleration exposures. Although the mechanism(s) of this effect has not been completely determined, it does appear that modifications of factors supporting circulation (possibly involving the baroceptor system) probably occur. Once these modifications are established, the rate of loss in animals of this "adaptation" without significant G exposure is quite variable, but as suggested for humans, appear to begin after about 2 weeks.

Regarding operations, frequent flying (certainly at least once a week) allows pilots to maintain a reasonable level of G tolerance. Not being exposed to significant levels of G for an extended period of time (e.g., a month) suggests that some "readaptation" to the environment should be allowed to occur. Certainly, a pilot should not, after a lengthy period of G inactivity, resume flying with an immediate vigorous ACM exposure. In Chapter 9, it is recommended that centrifuge G training be repeated in pilots who have not flown for considerable lengths of time.

G-PROTECTION METHODS

The relaxed ROR G-level tolerance of an individual seated upright (primarily $+G_z$ exposure) is about 4 G (Table 3-1). Since pilots are expected to fly high performance aircraft with 9 G capability, G tolerances must be increased by approximately 5 G. This increase is accomplished using the anti-G suit that accounts for about 1 G increase and the anti-G straining maneuver (AGSM) that increases G tolerance by 4 G. These operational methods to increase G tolerance are standard throughout the world, although some differences in the manner in which the AGSM is performed have been reported for the USSR and China (see a later section in this chapter on the AGSM).

Anti-G Suit Valve

The first "anti-G suit" was an inflatable abdominal belt developed in 1932 by Dr. Cecil Drinker, Harvard School of Public Health, and Lt Cdr John Poppen, U.S. Navy Bureau of Aeronautics. The "Poppen Belt" was tested on dogs and finally on humans, but the G protection provided was small so research was discontinued (159).

Early in World War II (WW II) the need to increase G tolerance of Allied pilots by as little as 1 G was acknowledged. Three research groups, each from a different country, began independently to develop an anti-G suit. In Australia, Professor F. S. Cotton developed a non-stitched fabric pneumatic suit that increased G tolerances by about 30%. The "Cotton" suit was flown by American fighter pilots in the Pacific and Europe. In Canada, Dr. W. R. Frank invented an anti-G suit that was filled with water that offered an increase of 1 G. The Frank's Flying Suit (FFS) saw limited combat in Europe (5). In the U.S., several types of anti-G suits were developed, but the 5 bladder inflated anti-G suit prevailed and is the forerunner of the current operational anti-G suit. This early anti-G suit was developed by David M. Clark (a manufacturer of cloth and underclothing) in close association with Drs. E. J. Baldes and Earl Wood of the Mayo Clinic Acceleration Research Group.

The current operational anti-G suit has a 5 bladder system and cut-away style. This bladder system is covered by a fire-retardant cloth fabric. The suit is zipped onto the body and, with lacing, allows for minor body size adjustments that can be accommodated with only 4 to 6 different sizes. The suit must be fitted snugly to the body so that the maximum benefit is obtained from pressurization of the bladders (Fig. 3-10).

Air from the jet engine is used to inflate and pressurize the anti-G suit. Pressure for the anti-G suit is controlled by a G-sensitive mass loaded valve that increases pressure proportional to G-field intensity. Although anti-G valves that are electronically controlled have been developed, the mass/weight mechanical anti-G valve remains in operations— primarily because of its simplicity, reliability and low cost. The anti-G valve is attached to the anti-G suit by a flexible hose. Specified air pressure as provided by this valve will not operate in G fields less than 2 G—so it is not activated during aircraft buffeting and moderate turns. However, at 2 G, air pressure is provided at 1.25 to 1.5 psi (8.6 to 10.4 kPa) per G, depending on its type, to a maximum of approximately 10 psi (69 kPa). These suit pressures must be fairly precise since less pressurization levels decreases the effectiveness of the G-suit, and greater pressures make the suit uncomfortable for the pilot.

Three major "brands" of anti-G valves are operational in NATO—each developed by a different country and

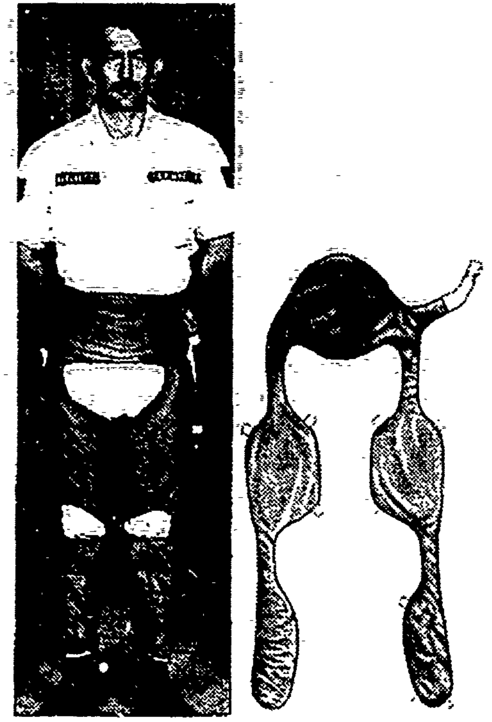


Fig. 3-10
A USAF operational anti-G suit shown with air bladders that are situated inside the suit for providing pressure to the body. The hose, shown connected to the suit, attaches to the anti-G valve inside the cockpit.

manufactured by a different company:

(a) Alar is the standard U.S. valve that has standard (STD) and high flow (HF) models;

(b) Hymatic (VAG 110) is a U.K. product with the model 110 most commonly used; and

(c) Intertechnique (French EROS) is designed and built by the French.

The operational characteristics of these valves are quite different, although the anti-G suit pressurization schedules are similar. Since the ability of the anti-G valve to provide the desired anti-G suit pressure fast enough to be effective is the most important factor, these values are presented for comparison for each valve in Figure 3-11.

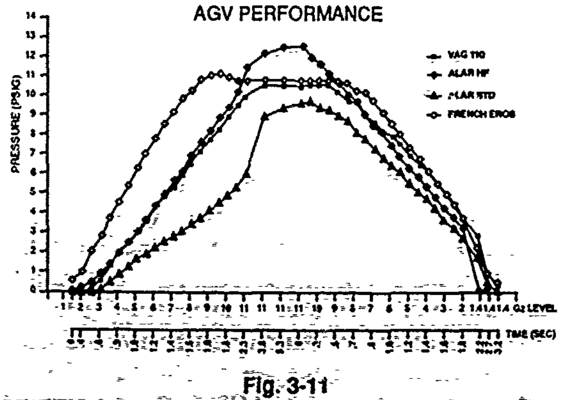


Fig. 3-11
Performance (anti-G suit inflation pressures, PSIG, related to G level and time at approximately 6 G/sec onset rate) is compared for major NATO operational anti-G valves (147,148).

The rapidity of anti-G suit inflation required to obtain the maximum increase in G tolerance is, of course, an important consideration (38). The increased relaxed G-level tolerance provided by the anti-G suit requires its inflation to a significant suit pressure (5 psi, 34.5 kPa) by 3.3 sec after reaching the G level using 6 G/sec onset rates. To maximally support the AGSM required at higher G levels (7 G at 6 G/sec) the equivalent figure was 2.8 sec. This study concluded that to allow for individual variation as a safety margin the anti-G suit must be inflated by 1 sec after reaching the immediate G level at a 6 G/sec onset rate (38). It appears therefore that extremely rapid anti-G suit inflation is not necessary; i.e., faster is not necessarily better since there appears to be a limit to the G tolerance offered by the rapidity of anti-G suit inflation. Similar studies are required as this conclusion will affect designs of future anti-G valves.

The most important physiologic function that increases relaxed G-level tolerance with the anti-G suit is an increase in Pa. At 4 G, this increase is approximately 15 mmHg that occurs because of a similar relative increase in vascular resistance. This increase in Pa accounts for about 0.7 G increase in G tolerance or approximately 50% of the increased G value of the suit. The other half increase in G tolerance comes from the reduction in the eye-heart vertical distance of 3 cm—raising the heart and diaphragm with the inflation of the abdominal bladder. This reduction of 3 cm at 5 G has the same effect as increasing the Pa by approximately 11 mmHg or about 0.5 G (37,165). The least effective cardiovascular support provided by this anti-G suit is in the cardiac output and stroke index parameters that show where improvements can be made in the design of this suit to provide better support for venous return.

The relative contribution of the various elements of the pneumatic G-suit in enhancing G-tolerance has been determined (45,217). As noted in the previous paragraph, the majority of increase in relaxed G-level tolerance comes from the abdominal bladder. Pressurization of the legs accounts for only 0.2 G—this tolerance increase is additive to the increased tolerance contribution of the abdominal bladder. A proper fit anti-G suit without pressurization will increase relaxed G tolerances by 0.3 G that is additive to the increase in G-level tolerance from inflating the suit (45). The approximate 1-1.5 G protection provided by the anti-G suit is independent of (additional to) the 1 G protection from the baroceptor response (GOR tolerance).

The effect of the operational anti-G suit on fluid shifts below the heart in the abdominal, thigh, and calf regions of a subject during a GOR to 5 G without the suit and 7 G with the suit is shown in Figure 3-12. Without the suit, an increase in fluid volume of nearly 10% occurs below the heart, whereas, with anti-G support this fluid shift is reversed with a net reduction in fluid shift at 7 G over 1 G controls. Some shift in fluid below the heart begins immediately with the onset of G even with the anti-G suit that, of course, has not begun to inflate until 2 G. However, before 3 G is reached, the anti-G suit begins to reverse the shift of fluid below the heart.

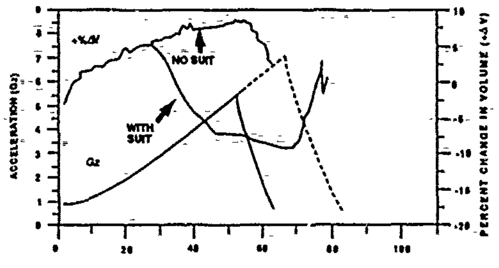


Fig. 3-12
Percentage change in fluid volume below the heart during a GOR to 5 G without, and 7 G with the USAF operational anti-G suit (126).

The value of different body coverage and anti-G suit pressurizations on G-duration tolerances was measured using the 4.5/7 G SACM maneuver until the subject became fatigued (170). Increased coverage of the legs with more uniform pressurization increased SACM tolerances by 133% (reduced fatigue) over the current anti-G suit. Improved venous return, in support of cardiac output, was considered the reason for reducing fatigue with this suit. During the SACM with uniform leg protection, maximum heart rates of only 154 bpm were found compared with 172 bpm using the standard anti-G suit (170). The application of this suit to future Air Force operations is discussed in the next chapter.

Anti-G Straining Maneuver (AGSM)

The use of muscular tensing and increasing the intrathoracic pressure by pilots to increase their Pa that results in an increase in their G-level tolerance appears to have originated in France in about 1924. However, the inflight application of a muscle straining maneuver for increasing G-level tolerance should probably be attributed to Stainforth of England in 1933.

He reported that with abdominal and leg muscle tensing, G tolerance could be increased by 2 G (of course without the use of the anti-G suit, since it hadn't been invented yet). He also recognized that if this straining maneuver was not interrupted frequently, venous return would rapidly decrease because of interference of venous blood flow to the right side of the heart (194). This maneuver, however, was not adequately developed and validated so that it could be routinely used in military flight operations.

At the beginning of WW II, it became apparent that pilots of fighter aircraft did not have sufficient G-tolerance to prevent blackout and G-LOC during high-G maneuvers (e.g., propeller powered fighter aircraft were capable of 6-7 G for brief durations and the U.S. P-51 Mustang used towards the end of WW II could pull 10 G for 3 sec duration). Consequently, the U.S. Army Air Corps sponsored a research team headed by Drs. Baldes and Wood at the Mayo Clinic, in 1941, with a human-use centrifuge to address this problem. From that group came a voluntary muscular tensing effort (similar to Stainforth's maneuver), but with coordinated forced exhalations against a partially closed glottis that they called the M-1 maneuver that significantly increased G-level tolerances. This maneuver that was used for brief durations of high G was taught to Allied pilots by instructing them to yell "hey" repeatedly (217). The L-1 maneuver was developed in the late 1970s at USAFSAM and is a variation of the M-1 found more useful with less throat irritation for long duration G exposure. In the L-1, the forced exhalations are against a completely closed glottis. These maneuvers, together with other modifications, are now simply called anti-G straining maneuvers (AGSM).

The AGSM involves a forced exhalation against a partially or completely closed glottis with straining of limb and abdominal muscles just before and during HSG. The exhalation (increased intrathoracic pressure) is maintained for 3-4 sec and is interspersed with rapid inspirations less than 1 sec; the process is repeated cyclically. It is an effective anti-G procedure, increasing the mean G-tolerance by as much as 4 G. The duration for which an effective AGSM can be applied is limited by fatigue. As fatigue develops and the maximum contraction capability of the required muscles fall, G-level tolerance decreases. The G-duration tolerance therefore is determined by the anaerobic capacity and muscle strength of the pilot. The importance of physical conditioning relative to G tolerance and its metabolic aspects will be discussed in Chapter 7.

Simply tensing arm, leg, and abdominal muscles before and during HSG increases G tolerance 1-2 G. The maximum effect, however, requires several seconds to occur since it is based on a reflex increase in Pa from simple isometric contractions (141). Both the AGSM and simple muscle tensing are effective with or without the use of an anti-G suit, although the inflated anti-G suit probably allows a pilot to perform the AGSM more effectively.

The respiratory aspects of the AGSM are an adaptation of the Valsalva Maneuver in which a high intrathoracic pressure is maintained by a single sustained contraction of the diaphragm and respiratory muscles against a constant resistance. This maneuver is the basis for the clinical Valsalva Test that challenges the circulatory system to cope with a decreasing venous return, testing the integrity of the baroceptor and cardiopulmonary reflexes. Since the skeletal muscles of the arms and legs and those of the abdominal wall are not contracted during this test, venous blood becomes dammed outside of the chest. This situation results in a rapid decrease in venous return and cardiac output. Therefore, the Valsalva Maneuver can be very dangerous if used by a pilot to increase G tolerance (174).

Since the AGSM is a learned maneuver, it must be taught to pilots. Its importance in increasing G tolerance—at 9 G producing 80% of the increase in tolerance over the basic G tolerance of 4 G—in the high-G arena requires that pilots perform this maneuver in an extremely effective manner. Frequently, aircraft mishaps involving G-LOC occur because of an ineffective AGSM (52). Consequently, formal training of the AGSM using a centrifuge with a controlled G environment, has been instituted by several NATO countries, as well as in Sweden, Korea, and Japan. The NATO recommended training program is described in detail in Chapter 8.

The Soviets and Chinese use an AGSM that relies primarily on muscular contractions with less emphasis on the respiratory effort. Since the Soviets successfully fly aircraft capable of at least 9 G, their AGSM method must be effective, although physiologic studies of this maneuver have not been reported.

Physiological Response To The AGSM

The physiological basis for the AGSM is that intrathoracic pressures generated by the forced expiration are transmitted directly to the heart and are added to the pressure generated by cardiac contraction which provides an increased Pa at eye level (Fig. 3-13) by as much as 100 mmHg for a group of subjects (37,166,218).

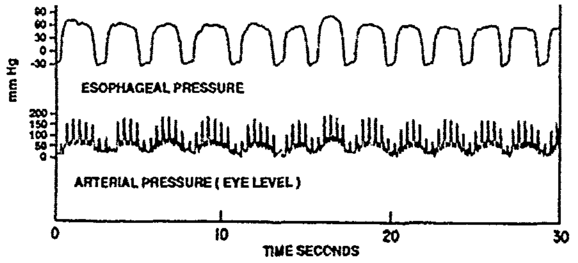


Fig. 3-13
Mean eye-level Pa and esophageal pressure changes during G of a subject while performing an AGSM during HSG. Mean Pa falls to near zero during the inspiratory phase. Esophageal pressure is a measure of intrathoracic pressure (47).

The AGSM, with increased intrathoracic pressure, tends to impair venous return. This problem is counteracted by tensing limb muscles, the pressures applied to the legs and abdominal cavity by the anti-G suit, and the repeated interruptions of the 3-4 sec forced exhalations with <1 sec rapid inhalations when Pa is greatly reduced (Fig. 3-13). To support the venous system for an adequate venous return, it has been shown that the anti-G suit pressure must be at least 4 times greater than the intrathoracic pressure. During routine G exposures, this level of anti-G suit pressure is always available—at 6 G when a maximum of 1 psi (6.9 kPa) AGSM is needed, anti-G suit pressure is about 6 psi (41.4 kPa).

The AGSM is capable of increasing G-level tolerance by 4 G allowing pilots to tolerate 9 G—4 G relaxed tolerance, 1 G increase for the anti-G suit, and 4 G for the AGSM. However, this amount of increase in G tolerance is only possible if the pilot is well trained in performing this maneuver, has adequate strength, and performs it optimally. It is not realistic to routinely demand near-perfection with a failure possibly meaning death. Therefore, it has been suggested that the current operational NATO anti-G system is adequate for sustained 7 G maneuvers (37). Consequently, methods to increase G protection by another 2 G are desperately needed. Fortunately, these are being developed, and are the subject of the next chapter.

SUMMARY

Human tolerance to G has both G-level and G-duration parameters. The limiting criteria for G-level tolerance are blackout and loss of consciousness. G-duration is limited by fatigue at levels above 3 G. An individual's basic G-level tolerance seated upright and relaxed is approximately 4 G at 1 G/sec onset rates, and some 0.3 G less at 6 G/sec. Slower onset rates of 0.1 G/sec increase tolerance by about 1 G from a baroceptor response. Current operational methods used by pilots to tolerate G levels of up to 9 G include the anti-G suit and anti-G straining maneuver (AGSM). The operational anti-G suit increases G-level tolerances by about 1-1.5 G. The AGSM is a forced "exhalation" against a closed or partially closed glottis with abdominal and limb muscle tensing that is interrupted every 3-4 sec with a rapid inspiration (breath) of 1 sec or less. The AGSM, if performed properly, can increase G-level tolerances by 4 G. Since this maneuver is fatiguing, the amount of time that a pilot can tolerate high G is rapidly limited by fatigue. G-duration tolerance is measured on the centrifuge with a continuous cyclic low G-high G exposure until the subject terminates the run because of fatigue. The operational G-protective methods currently used by NATO pilots allow them to tolerate 9 G only, if they perform a maximal AGSM, though fatigue rapidly occurs and their G tolerance falls. Consequently, the present G-protective systems that are considered adequate for 7 G maneuvering are inadequate for modern 9 G aircraft.

TOLERANCE AUX ACCELERATIONS +Gz ET METHODES HABITUELLES DE PROTECTION ANTI-G.

La tolérance humaine aux accélérations +Gz est fonction de leur durée et de leur niveau. Les limites de tolérance sont le voile noir et la perte de connaissance. Le temps de tolérance à des accélérations supérieures à 3 G est limité par la fatigue. La tolérance moyenne aux accélérations est de 4 G pour une mise en accélération de 1 G/s lorsque le sujet est à la fois décontracté et assis avec un dossier en position verticale. Cette valeur de 4 G est diminuée de 0,3 G lorsque la mise en accélération est de 6 G/s. Des valeurs de mise en accélération inférieures à 0,1 G/s favorisent une augmentation du niveau de la tolérance de 1 G grâce à la réponse des barorécepteurs. Les méthodes opérationnelles employées actuellement par les pilotes pour atteindre des accélérations jusqu'à 9 G comprennent le pantalon anti-G et la manoeuvre anti-G (AGSM). Le pantalon anti-G augmente la tolérance de 1 à 1,5 G environ. La manoeuvre anti-G consiste en une expiration à glotte fermée ou partiellement fermée s'accompagnant d'une contraction des muscles des cuisses et de l'abdomen. Cette contraction est interrompue toutes les 3 à 4 secondes par une inspiration rapide (<1 s). Une manoeuvre anti-G correctement effectuée peut augmenter la tolérance aux accélérations +Gz de 4 G. Etant donné le caractère fatigant de cette manoeuvre, son efficacité est limitée dans le temps. La tolérance des pilotes aux fortes accélérations diminue alors. Les méthodes opérationnelles de protection anti-G actuellement employées permettent aux pilotes de l'OTAN de supporter 9 G dans la mesure où ils effectuent une manoeuvre anti-G de très bonne qualité. Comme cette manoeuvre est fatigante, la tolérance aux accélérations diminue. En conséquence, on considère que les systèmes actuels de protection anti-G sont suffisants pour des évolutions à 7 G et insuffisants pour des évolutions à 9 G.

CHAPTER 4
POTENTIAL +Gz PROTECTION METHODS

INTRODUCTION

Today's fighter aircraft are capable of generating high and sustained levels of headward acceleration (+G_z; the symbol G will be used throughout to denote +G_z) and achieving these at high rates. A level of 9 G can be reached within one second. Current aircrew G protection systems allow peripheral vision in the unprepared pilot to fail at only 4-5 G. To increase G tolerance above that provided by the anti-G suit alone, anti-G straining maneuvers (AGSM) are performed by the pilot. These can increase his tolerance to 8 or 9 G, but require mental concentration and are physically fatiguing. Clearly, additional methods of G protection are needed.

This chapter will review developments and recent experimental findings in the traditional forms of G protection and describe additional methods that may improve man's tolerance to G. Most of this work was accomplished in human centrifuges. Historical reviews (56,110,217) and recent discussions of G protective techniques (8,47,128) are available.

Definitions of G tolerance and its assessment are described in Chapters 3 and 8. A useful and general definition of G tolerance would be the ability of man exposed to G to maintain consciousness and at least a minimum field of vision compatible with useful psychomotor performance.

It is well established that problems of visual impairment and loss of consciousness in an upright sitting individual on exposure to high levels of headward acceleration are due to decreases in blood pressure at head level (217). In turn, this is due to the hydrostatic distance between the eyes and heart, and slight hypotension at heart level secondary to blood pooling in the venous system in dependent regions. Attempts to increase tolerance to sustained G may approach the problem by: (a) directly increasing arterial blood pressure at the level of heart and eyes; (b) reducing the hydrostatic distance between heart and eyes; and (c) increasing blood pressure at heart level through reductions in venous pooling.

Techniques for directly increasing blood pressure are: (a) positive pressure breathing during G (PBG, introduced in Chapter 2), and (b) hypertensive agents such as carbon dioxide in the inspired gas or pharmacologic means. (To facilitate the association with blood pressure, PBG levels will be expressed in units of mmHg. For conversion, 7.5 mmHg = 1 kPa.) AGSM were described in Chapters 2 and 3 and will not be discussed in depth here. Techniques for reducing the hydrostatic heart-eye distance are: (a) reclination of the seat back; and (b) use of the prone position. Techniques for reducing venous pooling are: (a) G-suits with greater body coverage; (b) improved G-valves; and (c) elevation of pelvis and legs. The protection provided by the traditional G-suit was already described in Chapter 3.

POSITIVE PRESSURE BREATHING

Positive pressure breathing is the application of pressure by a regulator to the breathing gas throughout the respiratory cycle. It is being used operationally for emergency hypoxia protection on exposure to altitude above approximately 12,000 meters. For positive pressure breathing to be effective, the oronasal mask-to-face seal must be adequate to prevent excessive gas leakage. Positive pressure breathing at levels up to approximately 30 mmHg are acceptable, but induce fatigue at 1 G because forceful muscle contraction is required for expiration. "Balanced" positive pressure breathing is the additional application of counter-pressure to the chest with a jerkin or vest. As the jerkin is pressurized by the same hose leading to the mask, this pressure will counter-balance any increased pressure in the lungs. This limits lung expansion and reduces fatigue by assisting expiration. With a jerkin, the level of positive pressure breathing may be as high as 60-70 mmHg. (In this chapter, positive pressure breathing and PBG are to be assumed to be without chest counter-pressure. If balanced pressure breathing is being referred to, it will be so stated.)

The G protective benefits of PBG are similar to those of the AGSM. The increased intra-pulmonary pressure is transmitted to the left ventricle and intra-thoracic vessels, and results in an increase in systemic arterial pressure. The high intra-thoracic pressure may impair venous return and then decrease systemic blood pressure unless a G-suit maintains the pressure gradient between peripheral venous and central venous blood pressures. Although PBG had been used experimentally as early as 1944 (131), optimal methods of use and extent of its effects were unknown, and the procedure required substantial development.

Lowry et al (142) studied PBG levels up to 25 mmHg. Their subjects increased visual threshold by 0.5 - 0.9 G compared to the normal G-suit condition without PBG.

Chambers et al (55) used a PBG schedule of 1.4 mmHg/G up to 5 G with pure oxygen. Compared to regular breathing of air or oxygen, visual brightness discrimination requirements were significantly lower at 3 G with oxygen PBG, and there was a general ease of breathing and comfort.

Shubrooks (175) compared the M-1 AGSM and PBG at 40 mmHg in conditions with G-suit inflation or abdominal and leg tensing. PBG did not change the G level at which peripheral light loss (PLL) was experienced during rapid onset rate (ROR, 1 G/sec) G profiles in the centrifuge. The subjects completed 45 sec at 8 G with the M-1 or PBG, but they experienced less physical work with PBG. PBG also reduced the inspiratory-induced decreases in arterial pressure seen at eye level with M-1, and overall arterial pressure was more sustained with PBG.

A collaborative effort by USAFSAM and RAF-IAM (70,136) studied a series of 60 sec exposures at 3, 6 and 8 G with the subjects using the M-1 or PBG (PBG 28-30 mmHg when G > 2 G). There was no difference in G tolerance with PBG compared to the M-1 but PBG was less fatiguing, and at 3 and 6 G, the partial pressure of oxygen in arterial blood was greater with PBG.

Glaister and Lisher (99) flight tested PBG after observing in the centrifuge that PBG at 5 mmHg/G (G > 2 G) augmented relaxed G tolerance by 0.8 G above that offered by the G-suit. The Type 517 breathing regulator was modified to cut in at 2.5 G with 12.5 mmHg of mask pressure. Mask pressure increased by 5 mmHg/G to a maximum of 35 mmHg. With sorties attaining 6 G, the pilots found PBG acceptable and less tiring than the M-1. Speech was difficult, but with practice became intelligible. It was felt that PBG was not needed below 4 G.

Balanced positive pressure breathing was first studied as a G protective technique by Shaffstall and Burton (169) using 30 mmHg in conditions: (i) with USAF G-suit; (ii) with RAF jerkin and USAF G-suit; (iii) with CF waistcoat-type jerkin and USAF G-suit; and (iv) with Swedish combination G-suit and chest counter-pressure garment. In relaxed, gradual onset rate (GOR) (1 G/10 sec) profiles, all PBG conditions increased G tolerance compared to the control tests with the G-suit only. For the simulated aerial combat maneuver (SACM) profile, in which G cycles repeatedly between 4.5 and 7 G, tolerance time using balanced PBG was 27% greater than in the G-suit and straining control tests. Tolerance time with unbalanced PBG was not different from control. It was felt that without a jerkin, pressure breathing with 30 mmHg could promote fatigue due to constant expiratory muscle activity. Therefore, unbalanced PBG may be no more effective than the M-1 for G tolerance, but balanced PBG may be advantageous by reducing fatigue. Heart rate and oxyhemoglobin saturation were not different among the conditions.

Shaffstall and Burton (171) used profiles to 7 G to study tolerance time, heart rate, and performance in a tracking task in different PBG conditions: (i) control (no PBG); (ii) PBG 5 mmHg/G starting at 1 G and maximum of 30 mmHg at 7 G; (iii) PBG 5 mmHg/G starting at 4 G with maximum of 15 mmHg at 7 G; (iv) PBG with cut-in 17.5 mmHg at 3.5 G then 5 mmHg/G to maximum of 30 mmHg at 7 G; and (v) PBG with 30 mmHg continuous and starting before G. These schedules using unbalanced PBG did not improve G tolerance compared to the M-1, nor reduce the fatigue involved in maintaining vision and consciousness.

Using a SACM profile (5-9 G with 10 sec plateaus), Burns and Balldin (33) studied three experimental conditions: (i) control (G-suit and AGSM); (ii) CF jerkin-balanced PBG 50 mmHg (cut-in at 1.2 G and increasing linearly to maximum of 50 mmHg at 9 G); and (iii) balanced PBG 70 mmHg (cut-in at 1.2 G and increasing to maximum of 70 mmHg at 9 G). The profile end-points were light loss, fatigue or discomfort. With AGSM as necessary for maintenance of vision, tolerance time in SACM increased by 115% with balanced PBG of 50 mmHg compared to control. With balanced PBG 70 mmHg, time increased by 88%. There was no difference in hemoglobin saturation at end of SACM or sustained 9 G, but saturation did not decrease as quickly with PBG 50 mmHg. Heart rate was not altered. Although PBG 70 mmHg should theoretically have provided the best protection with the greatest intra-thoracic pressure, uncomfortable nasopharynx distension and tightly fitted masks possibly shortened duration. PBG increased the inspired volumes and hemoglobin saturation was likely improved due to a better matching of regional ventilation and blood flow in the lungs.

Domaszuk (72) investigated constant PBG levels of 15, 30, 45 and 60 mmHg in GOR profiles using a pressure helmet and full capstan-like suit (no additional G-suit). Compared to the relaxed control G tolerance, the four levels of PBG increased tolerance by 0.4, 1.8, 2.2, and 1.7 G respectively. PBG of 60 mmHg was uncomfortable and 15 mmHg was undetectable. In his second study, 45 mmHg PBG was delivered in a G profile increasing at 0.2 G/sec then continuous at 5 G. PBG increased the duration of this test to 266% of control and reduced the heart rate.

Bagshaw (7) conducted flight trials with a PBG schedule of 5 mmHg/G, starting at 4 G during increasing G, and terminating at 3 G during decreasing G. The press-to-test facility of the oxygen regulator was modified to deliver 100% oxygen during PBG, but deliver airmix before and after G. With instructions that straining could be added if needed, 71% of pilots felt that PBG increased tolerance to air combat maneuvers and was more effective than AGSM. Less fatigue was felt afterwards. The abrupt cut-in/cut-out of PBG at 4/3 G was considered to be less than ideal.

Prior et al (163) found relaxed G tolerance, as indicated by visual criteria, was increased by 0.42 and 0.36 G by PBG and balanced PBG, respectively, compared to the G-suit only tolerance level of 5.55 G in ROR profiles. PBG was delivered at approximately 10 mmHg/G starting at 4 G. This PBG system was unique in that the breathing regulator received a pneumatic signal from the anti-G valve outlet. On pressure from the anti-G valve, PBG would start. In PBG systems with independent G-sensitive devices, pressure breathing syncope could develop if there is not simultaneous G-suit inflation.

Harding and Cresswell (104) reported favourable comments from Hunter aircraft pilots testing PBG at 10.85 mmHg/G (from 0 mmHg at 2.3 G to 51 mmHg at 7 G). Chest counter-pressure was a further advantage. Follow-up trials in the Hawk aircraft showed that balanced PBG (6 mmHg/G with 13 mmHg at 3 G to 45 mmHg at 8 G) provided significantly more anti-G protection than unbalanced PBG or G-suit and straining alone.

In early 1987, USAF conducted flight trials in an F-15 aircraft fitted with prototype balanced PBG systems designed to assess their G protective capability and effects on aircraft operation. This technology had been developed from the work of Burns and Balldin at USAFSAM using

50 and 70 mmHg balanced PBG. The maximum pressure level was 60 mmHg at 9 G. The three pilots strongly endorsed PBG as an anti-G system, feeling that they were well-protected and probably could tolerate G loadings for longer durations and at greater than present limits. The prototype PBG systems, however, limited pilot mobility and comfort.

In flight trials with PBG of 13 mmHg at 3 G to 45 mmHg at 8 G, Cresswell et al (68) found, according to subjective evaluations, balanced PBG to be significantly more effective at G protection than unbalanced PBG or straining alone.

Clère et al (59) evaluated constant balanced PBG levels of 38, 53, and 68 mmHg in relaxed GOR tests taken to 50% PLL. When PBG was applied at 2 G, the three pressures increased tolerance by 1.45, 1.5 and 2.5 G, respectively, compared to the G-suit only control test. Tolerance was increased by 1.83, 2.2, and 2.43 G, respectively, when PBG was applied once the subject had 50% PLL. PBG of 68 mmHg always restored the full visual field. It was recommended that PBG should increase gradually from 4 G and that 68 mmHg offered the best protection.

Balldin et al (11) studied balanced PBG employing a pressure schedule of 10 mmHg/G, starting at 4 G with a maximum of 50 mmHg at 9 G. The seat back angle was 30 degrees. In relaxed GOR tests, the proportion of subjects enduring 9 G for 10 sec increased with PBG from 18 to 82%. In ROR tests using AGSM as needed to avoid visual grey-out, the proportion increased from 71 to 100%.

Presently, PBG is regarded as an important addition to the G protection system. By increasing intra-thoracic pressure, PBG reduces the fatigue associated with the AGSM when assistance is provided by external thoracic counterpressure. Also, by providing increased pressures automatically with elevations in G, the pilot should be less concerned with adjusting the intensity of his straining effort. A more alert and less fatigued pilot should be able to maintain concentration on his flying tasks. Issues that remain to be resolved are the ideal PBG pressure/G schedule, the G level for PBG to cut in and out, and suitable headgear to maintain the appropriate pressures. As PBG will be introduced into service in 50 USAF F-16 aircraft in the early 1990's and probably incorporated in the new European Fighter Aircraft, facilities and programmes for training aircrew on the use of PBG will be needed.

HYPERTENSIVE AGENTS

Carbon dioxide may improve G tolerance because it is known to cause systemic vasoconstriction and cerebral vasodilation. Early reports by Ruff in 1938 and Matthes in 1940 suggested that G tolerance is increased by 0.5 G with inspirates of 4-6% carbon dioxide (82).

Brachial arterial pressure of dogs and monkeys at 6 G was increased by approximately 20 mmHg with 13% carbon dioxide compared with control (189). With 20% concentrations, the blood pressure was 45 mmHg greater. It was necessary for carbon dioxide to be inhaled for at least 30-60 sec before, and continued through, the acceleration period. Because some of the blood pressure benefits were associated with increased pressure at 1 G, redistribution of blood volume was speculated as a further effect of carbon dioxide. The gas provided no G protective effect when given in concentrations of 5-10%. Any protection was less if carbon dioxide was breathed for more than 7-12 min.

Krutz (123) found that human volunteers breathing 5.2 and 7.9 % carbon dioxide increased G tolerance by 0.51 and 0.88 G, respectively, compared to air breathing control values. The ROR profiles were conducted in the relaxed mode.

Glaister (93) observed that relaxed G tolerance for GOR and ROR profiles increased by 0.8 and 0.9 G, respectively, when the inspirate contained 5% carbon dioxide and was given 2 min before the tests. With 7% carbon dioxide, tolerance was further increased by 0.4 and 0.7 G, respectively. Carbon dioxide however caused breathing discomfort and extreme headache.

Howard (110) reviewed the effect on G tolerance of pharmacologic agents that theoretically could increase vasomotor tone and/or blood pressure. Generally, their effect is negligible. A list of tested drugs includes: analeptics, adrenaline, adrenaline and ephidrine, atropine, amphetamine sulphate, anti-malarial agents, oestradiol and testosterone, paredrine, and sodium diphenylhydrantonin. Adrenocorticoids and posterior pituitary extracts also failed to improve G tolerance.

RECLINED SEATS

As one factor determining blood pressure at head level is the vertical height between the head and heart, reclining the seat back away from the vertical will result in greater blood pressure at this site.

Crossley and Glaister (71) studied back angles of 70, 45, 30, 25, 20 and 15 degrees from the horizontal. At 70 degrees from the horizontal, GOR and ROR tolerance levels, determined by PLL, were 4.5 and 3.3 G, respectively. The tolerance levels were 7.3 and 5.7 G, respectively, at 15 degrees. The grey-out threshold was found to be proportional to the inverse of the vertical eye-heart distance (distance calculated as the sine of seat back angle from the horizontal) and the threshold was significantly improved when the back angle was 45 degrees or less from horizontal. Wearing a G-suit further increased relaxed G tolerance even though the thighs were positioned above, and the heels positioned level with the hips. This action may have been due to an increase in peripheral vascular resistance. It was concluded that the near supine position with a G-suit can provide relaxed thresholds between 6-8 G while permitting adequate forward visibility.

Burns (31) found no difference in G tolerance between the control seat back angle of 13 degrees from vertical and

30 degrees. At 45 degrees from vertical, tolerance increased by 0.5 G. At 75 degrees, the tolerance of 8 G represented a 100% increase over the control level. The thighs and legs were below hip level. Heart rate and the intra-thoracic pressure required to maintain the visual field were decreased with greater seat back angles. Tolerance was again highly correlated with the inverse of the eye-aorta distance.

A reclined seat produces a greater $+G_x$ component on the body with greater respiratory difficulty during G, therefore Glaister and Lisher (98) used PBG to help raise the anterior chest wall. With a PBG schedule of 5 mmHg/G to 35 mmHg maximum, the relaxed grey-out threshold of 3.49 G in the conventional seat was increased to 4.89 G with the seat angled 65 degrees from vertical. As found earlier, the addition of the G-suit increased G threshold and each increment of pressure in the G-suit schedule added protection. The normal expiratory reserve volume at 1 G was maintained at 4 G with PBG, suggesting that a similar work of breathing was restored.

Gillingham and McNaughton (87) used visual field limit tracking during relaxed GOR profiles to 7 G. Complete visual loss occurred at or near 5 G when the seat back angle was 13 degrees from vertical. At 45 degrees, there was complete visual loss at or near 6 G. When the seat back was at 65 degrees, substantial vision remained at 7 G.

Glaister and Lisher (100) utilized a psychomotor performance test with a high motor demand to assess the benefits of reclination to 60 degrees from the vertical compared to 17 degrees. With a pressurized G-suit and PBG at 5 mmHg/G to a maximum of 40 mmHg, performance at 6 and 8 G improved in the reclined seat, equivalent to 1-2 G of additional protection. Heart rate was similar at 8 G reclined compared to 5 G upright.

Following-up with a psychomotor test with greater mental effort, Lisher and Glaister (140) studied seat back angles of 17, 52, and 67 degrees from vertical. Compared to the 17 and 52 degree positions, 67 degrees raised the acceleration level at which a performance decrement occurred by 1.4 G.

Glaister (92) reviewed published data on the effect of seat back angle on G tolerance in relaxed and unprotected, protected with G-suit only, and G-suit with straining or PBG conditions. G tolerance in each condition was described by a different mathematical relationship but all were proportional to the inverse of cosine of the angle of seat back and the G vector. Independent of the condition, the regressions predicted that seat back angles of 58, 69 and 74 degrees would deliver 1, 2 and 3 G increases in grey-out tolerance, respectively, compared to the upright seat. Tolerance would be further increased by 1.21 G with the G-suit and by 3.15 G with full protection from the G-suit and straining or PBG.

Burton and Shaffstall (49) measured increases in endurance time of 38, 98, and 218% in the SACM profile when the seat back angles were 30, 55 and 65 degrees from vertical, respectively, compared to the control value at the 13 degree position. Heart rate 120 seconds into the profile was significantly less at the 55 and 65 degree angles.

Cohen (64) reported that seat reclination to 75 degrees increased relaxed G tolerance by 3.12 G. If used with a G-suit and/or straining maneuver, reclination offered the same increase in protection.

Burns and Whinnery (35) radiographically measured the hydrostatic distance between the eye and aortic valve at seat back angles of 30 and 65 degrees from vertical, each posture with a headrest geometry of 12, 25 and 45 degrees up from the reclination line. Relaxed G tolerance significantly correlated with the inverse of this hydrostatic distance. While headrest geometry had no effect on G tolerance at a seat back angle of 30 degrees, lowering the head from 45 to 12 degrees at the 65 degree back angle, increased mean tolerance by 1.7 G. Nelson (155) has calculated that the aortic valve is the most appropriate reference position for the hydrostatic theory of visual blackout.

G tolerance is significantly improved with seat reclination beyond 45 degrees from the vertical but the position causes practical problems (17,192) of vision difficulties and breathing impairment, and would require a re-design of the cockpit. PBG could alleviate the respiratory problems.

PRONE POSITION

Similar to reclination, the prone position augments tolerance to positive acceleration by decreasing the heart-eye hydrostatic distance. The increased protection was apparent in experiments performed in Germany and the U.S. in the late 1930's and early 1940's. Generally, vision was unaffected at 9 G sustained for 10 sec.

Clark et al (58) found that in the prone position, humans could tolerate up to $-12\ G_x$ (for definition of G_x, see Chapter 2). There were no visual symptoms when the head and trunk were level. Complete blackout occurred in some subjects at 10-12 G if the head was lifted 4-6 inches above the trunk.

The prone position however places excessive pressure on certain body points. Chin pressure and interference with speech were partly overcome by supporting the helmet with cable, pulley and counter-weight. Special couches alleviated the back and torso pressure. Breathing is more laboured in this position, although is not as difficult as in the supine position, and there can be pain in the extremities due to blood pooling in dependent regions, fluid drip from the nose, petechial rashes, displacement of the eyelids in the dependent direction, lacrimation, and salivation. Views in the upward and rearward directions remain seriously impaired.

Before acceptance of the G-suit, RAF efforts at improving G tolerance produced a modified Meteor test aircraft. One account described the prone-positioned pilot feeling quite fresh in contrast to the fatigued, upright check-pilot following an aggressive test sortie (132). 6 G was attained without the prone pilot experiencing black-out.

Ballinger studied tolerance to prolonged acceleration in semi-supine and semi-prone positions without G-suits (15). The duration of exposure varied from 15 min at 3 G to 2 min at 10 G, with little difference in tolerance between the two positions once the sources of physical discomfort were overcome. Even at the highest G levels, there was mental clarity and normal vision.

The prone position is preferred over the supine because there is less displacement of the heart and less over-distension of the lungs at high vertical G.

MODIFIED ANTI G-SUITS

In a significant investigation of G protection, Wood and Lambert (215) found that for every unit of increase in G, systolic blood pressure at heart level decreased 3 mmHg while diastolic pressure remained unchanged. At eye level, blood pressure decreases per G increase were 32 mmHg systolic and 19 mmHg diastolic. With a G-suit, systolic and diastolic blood pressure at heart level increased 5 mmHg per G increase, while at the level of the eye, the normal decreases were reduced to 20 and 14 mmHg, respectively. Later, it was found that the effectiveness of the G-suit to increase G tolerance improved with increases in lower body coverage to the maximum area provided by the standard five-bladder suit, and by greater inflation pressure (216). Water immersion also increased G tolerance (102). These observations are consistent with the principle that the G-suit should apply uniform pressure over as much of the lower body as possible.

The pressurized G-suit improves G tolerance through three modes of action: (i) increasing peripheral vascular resistance (139) by developing high tissue pressure in the lower limbs; (ii) preventing the normal descent of the diaphragm during G by supporting the abdominal wall; and (iii) limiting the blood volume collecting in the capacitance system of the abdomen and legs through the high counter-pressure. The first two actions contribute to limiting the decrease in arterial blood pressure at the beginning of exposure to G. By helping to maintain the central blood volume, the third action supports blood pressure during extended exposure to G.

The standard 5 bladder G-suit has been widely accepted because its design and inflation method were highly practical and because it offered G protection equivalent to the limits of the aircraft when combined with properly performed AGSM. However, efforts have been made to augment the protection provided by the lower body garment. Early ventures resulted in G-suit designs incorporating circumferential bladders (176) and principles from the lower half of a full pressure altitude suit (61,137,176). Such altered designs out-performed 5 bladder suits by approximately 1 G in relaxed G tolerance tests. This was achieved by increases in arterial pressure through greater increases in peripheral arterial resistance and maintenance of a greater blood volume in the thoracic viscera compared to the standard suit (176). Some of these full coverage suits were uncomfortably restrictive around the lower rib cage and abdomen, bulky, and required longer pressurization times. They may, however, need less pressure for equivalent protection (137).

Other versions of the early G-suit provided a gradient of counter-pressure from the ankles up to the trunk, or were designed to completely occlude the arterial inflow to the limbs (217). The former was technically complex and offered no greater protection than the single pressure, 5 bladder suit, while the latter, although significantly increasing G tolerance, caused ischemic pain in the arms and legs.

The capstan G-suit, which applies pressure to the skin through the tightening effect of inflated pneumatic levers, offered no extra protection for relaxed G tolerance compared to the standard 5 bladder suit (48). When the inflation pressure in the suits was increased, their performance remained comparable. In a subsequent investigation in which the counter-pressures exerted by the standard G-suit and a capstan suit were similar, SACM tolerance time with the capstan suit was increased by 133% (170). The difference in the relative effect of the capstan suit compared to the regular bladder G-suit in these two studies may have been due to a lower level of counter-pressure exerted by the capstans (127) in the earlier study.

Krutz and Burton (124) compared a modified CSU-4/P pressure suit designed to provide uniform lower body and abdomen pressurization through a full bladder, with the CSU-15/P G-suit using tests of incremental ROR G profiles until PLL. The full coverage G-suit increased G tolerance by 0.6 G. According to heart rate criteria, the full suit inflated to 34.5 kPa (6.89 kPa = 1 p.s.i.) at 6 G offered protection equivalent to 65 degrees of seat back reclination.

The Tactical Life Support System developed for USAF in 1987, in addition to providing PBG, incorporates more coverage by the five-bladder G-suit (29,149), the suit volume being increased by approximately 45%. As reported at the 1985 meeting of ASCC Working Party 61, limited centrifuge tests at USAFSAM comparing with the CSU-13B/P G-suit, demonstrated approximately 0.5 G improvement in tolerance with the TLSS G-suit combined with a faster G-valve.

Krutz and Burton (125) studied the standard five-bladder G-suit, a reticulated foam uniform pressure suit, and a pneumatic uniform pressure suit with bladders arranged to form a cylinder around the limbs. In GOR, very high G onset rate (6/sec), and SACM G profiles, the pneumatic uniform pressure suit provided more protection, increased endurance and was subjectively preferred compared to the other two suits. It was reasoned that the benefits were due to increased venous return and maintenance of peripheral circulation without pooling. Impedance plethysmographic measurements suggest that, while the standard G-suit limits the amount of blood pooling occurring in the lower body during G, the pneumatic uniform pressure suit further decreases the blood volume in the calves and thighs and displaces it upward to increase abdominal blood volume (126).

Balldin et al (10) observed that a full coverage lower body suit increased GOR tolerance by 0.4 G compared to the standard suit. Time to visual grey-out in SACM was longer with the full suit and some subjects could sustain 9 G for a short period without straining. With the full coverage suit, the peak heart rate was lower and less petechiae were observed, but hemoglobin saturation, ratings of perceived exertion and comfort were unchanged.

Prior (162) observed an increase in the relaxed G threshold for PLL from 5.2 G with the standard G-suit to 6.5 G with a G-suit that covered all body parts below the umbilicus, except the ankles and toes. When PBG was added according to a schedule of 9 mmHg/G, the threshold increased to 8.3 G. It was suggested that the gains might be largely due to coverage of the gluteal region. The full coverage G-suit was comfortable, but restricted leg mobility.

A retrograde-inflating G-suit could direct blood from the periphery toward the central regions. Delaying thigh, and then abdominal bladder pressurization either 1 or 0.4 sec after calf bladder inflation with a normal G-suit pressure/G schedule, actually decreased relaxed G tolerance by 0.4 G compared to the condition using the standard G-suit (44).

IMPROVED ANTI-G VALVES

The protection provided by the G-suit depends greatly on the G-valve pressurizing it. The G-valve must deliver the correct pressure at the correct time. Henry et al (107) altered the time at which G-suit inflation began relative to the attainment of 2.5 G during 15 sec centrifuge runs up to 5 G. G protection, according to PLL, was at its maximum when the start of inflation occurred within a range extending from approximately 10 sec before, to the moment coincident with passing through 2.5 G. G-suit inflation beginning 5 sec after reaching 2.5 G decreased protection by approximately 13%. This was lowered to 50% with a delay of 10 sec. The rate of G onset was approximately 3.4 G/sec above 2.5 G. Reaching 3 G was recommended as the latest point for starting G-suit inflation.

Until the 1970's, the performance of the G-valve was adequate. But in tactical fighters capable of sustained, high G maneuvers, and attaining high G at previously unattainable rates, the G-valve was a limiting factor to a pilot's performance. Since head-level arterial blood pressure begins to decrease immediately upon application of G, and one benefit of the G-suit is to provide hypertension at heart level which is achieved through increases in systemic vascular resistance, it is logical to expect that the G-valve should provide pressure coincident with the G profile. Surprisingly, the evidence is not conclusive on this issue.

Burton et al (48) found that inflating the standard G-suit to 6.9 kPa at the start of centrifugation, increased tolerance by 0.4 G in ROR profiles. This pre-inflation procedure pressurizes the G-suit approximately 3 sec ahead of the normal schedule.

In 1979, a mechanical G-valve (ALAR Products Inc.) that provided an increased flow rate, in addition to pre-acceleration inflation, was evaluated (50). Reducing the G-suit inflation times by approximately 75% in bench tests, subsequent centrifuge and flight tests rated it to have a high degree of acceptance, allow pilots to use less effort at high levels of G, and improve G tolerance by approximately 1 G over the standard valve.

An electronic G-valve has been developed in which the pressure to the G-suit is controlled by the voltage difference between the output of an accelerometer and a G-suit pressure transducer (69). The G-valve output pressure is able to track the G profile and results in a delay of only 0.5 sec in G-suit pressurization. In comparisons using very rapid G onset rates and 15 sec sustained G centrifuge profiles, the electronic valve improved G tolerance compared to the standard mechanical G-valve. The increases were 0.5 and 1.3 G with subjects in the relaxed and straining modes, respectively. G-suit pressure was developed according to $P=10.3\ (G-1)$ kPa, $(1.5<G<8.3)$, with a maximum of 75.8 kPa.

When G is greater than 2 G and the rate of onset is greater than 2 G/sec, a solenoid in an electro-mechanical valve opens for a set period, i.e. 1.5 sec, to maximally inflate the G-suit (190). The necessary G-suit pressure is then determined by the valve's standard, mechanical characteristics. This valve improved G tolerance by 1 G compared to the standard valve in relaxed subjects exposed to 15 sec constant G at 3 G/sec onset rate.

Cammarota (54) found that the ALAR high-flow G–valve, a rapid response servo valve, and a servo valve programmed to anticipate the onset of G by 500 ms, all offered similar protection for G tolerance in ROR profiles, and duration tolerance in SACM tests, but these were greater than the protection offered by the standard ALAR G–valve.

Burton (38) evaluated the allowable delay in G-suit inflation for light loss criteria to be significantly affected. Compared to the maximum inflation rate condition which would allow G-suit pressure to reach 34.5 kPa 0.2 sec before attaining 7 G, a mean delay of 3.3 sec had no effect on relaxed G tolerance with 6 G/sec onset rate to the final G plateau. With a 4.2 sec delay, light loss occurred earlier. In AGSM conditions with 6 G/sec to 7 G, a mean 2.8 sec delay decreased protection, but 2.0 sec did not. It was concluded that inflation of the G-suit could be delayed by at least 1 sec after reaching maximum G without compromising its protection.

Frazier et al (80) proposed that with microprocessor controlled anti-G valves, the G-suit pressure/G schedule need not necessarily be linear. At 3 G and under, where G-LOC is unlikely, pressure could be less than the Military Specification. Pressure could be greater than the specification if the G level was above 5 G where loss of vision and G-LOC were possible.

Jaron et al (113) developed a valve that pulsates the G-suit. Pressure in the various compartments of the G-suit is cycled between positive and negative excursions around the mean value equal to the standard G-suit pressure. In GOR and ROR G profiles, the best protection was obtained when all bladders were inflated simultaneously to a positive level during each cardiac systole. Thorough comparisons with standard protection have yet to be reported.

PELVIS AND LEGS ELEVATION

In addition to investigating various seat back angles, Voge (191) measured the effect of changing the position of the legs on PLL threshold. At a seat back angle of 45 degrees from the vertical, and the thighs at 59 degrees from vertical, there was no difference in G tolerance, 6.3 compared to 6.5 G, when the lower legs where at 115 degrees from vertical or hanging vertically, respectively. The addition of a G-suit increased the G tolerance in each position, in agreement with other findings (71). The greatest G tolerance, 11.1 G, was obtained with the seat back at 75 degrees and the thighs resting on the chest ("fetal" position), however this posture produced complaints of tiredness, pressure on the chest and legs, and general discomfort.

Approximately a 0.4 G increase in relaxed grey-out threshold can be achieved by elevation of the feet (172). This is believed to be a result of decreased vaso-dilatation and veno-distension in the lower legs. Others suggest that elevation of the feet has no anti-G benefits (42).

CONCLUDING REMARKS

Several methods of supplementing the G protection now provided by the 5 bladder G-suit and AGSM have been described. Carbon dioxide must be breathed before the G exposure, and the headache and breathlessness it provokes would be unacceptable features of flying, even if only in an anticipatory mode. No pharmacologic agent has demonstrated G protective value and there may always be the risk of undesirable side effects.

The usefulness of the remaining methods depend on whether the posture of the pilot can be altered. Changes in posture deal effectively with the single greatest reason for G intolerance, the heart-to-head hydrostatic distance. Indeed 10 G could be easily sustained. As the G protective benefits of G-suits, reclination, and increases in intrathoracic pressure can be combined according to an additive model, 11.8 G is predicted to be tolerated with a 55 degree reclined seat and a PBG/AGSM combination of 100 mmHg (37). But the price of reclination may be too great. Changes in posture require a redesign of the cockpit that is already too late for next generation tactical fighters. Vision out of the canopy and movement of head and limbs are impaired with the more horizontal posture. The respiratory system would become the G-limiting physiological system. PBG could assist breathing in different postures. Tolerance time at 10 G of forward acceleration was increased by 67% with 19 mmHg of PBG (195). Dyspnea, however, still remained the main reason for terminating the runs, even though the PBG level used was that preferred by the subjects.

Whether the seat back is upright or reclined, greater coverage G-suits and their faster inflation hold promise for improving G-tolerance. When combined with PBG, such a modernized anti-G system will confer great improvements in endurance to pilots at submaximal levels of G, and will make G-induced loss of consciousness less frequent in high intensity, short duration G. Importantly, such a system could be used in present generation aircraft. The challenge will be to make a greater coverage G-suit practical and to produce a reliable G-valve that will deliver the larger gas volumes when needed.

Whatever the form of the G protective system, the AGSM will be a major part of it, even with PBG, and particularly if anti-G equipment fails. The ability to perform a proper AGSM must not be taken for granted.

SUMMARY

To reduce the incidence of G-induced loss of consciousness and enable pilots to operate their aircraft at higher levels of performance, anti-G protection must be improved. A G-suit and the anti-G straining maneuver will likely remain essential components of any anti-G system, but several methods potentially increasing G-tolerance have been investigated that could supplement the protection afforded by these traditional techniques. Pharmacologic agents are of no benefit, while breathing carbon dioxide, shown to improve G tolerance, is impractical. Positive pressure breathing has so convincingly improved G-protection that it will become an operational procedure in the immediate future. The benefits of the G-suit have been augmented through greater coverage of the lower body and efforts are also aimed at more responsive G-valves. Altering body position to shorten the heart-to-head hydrostatic distance adds directly to the protection offered by the other procedures but can impair vision and must wait until the cockpit is redesigned.

METHODES POSSIBLES DE PROTECTION ANTI-G.

La protection anti-G doit être améliorée pour réduire l'incidence des pertes de connaissance liées aux accélérations et permettre aux équipages d'avion de combat de mener à bien leur mission opérationnelle à des niveaux d'accélération plus élevés. La manoeuvre anti-G et le pantalon anti-G restent toujours les méthodes essentielles de protection. Plusieurs autres méthodes pouvant augmenter la tolérance aux accélérations ont été étudiées et pourraient s'ajouter aux techniques classiques citées ci-dessus. Il n'existe pas d'agent pharmacologique ayant un effet positif sur la protection anti-G et d'un autre côté, l'inhalation de gaz carbonique, bien qu'améliorant la protection, n'est pas utilisable. L'amélioration de la protection anti-G par la respiration en pression positive est nette. Cette méthode deviendra opérationnelle dans un futur immédiat. L'efficacité du pantalon anti-G est accrue par l'augmentation des surfaces des vessies recouvrant la partie basse du corps et par la diminution du temps de réponse des valves anti-G. Les méthodes réduisant de façon notoire la colonne hydrostatique séparant le cerveau du coeur ajouteront de manière directe leurs effets bénéfiques à ceux des autres méthodes de protection anti-G. Cependant ces méthodes peuvent altérer la vision et il faudra attendre une nouvelle conception des cockpits pour les rendre opérationnelles.

CHAPTER 5
G-INDUCED LOSS OF CONSCIOUSNESS (G-LOC) INCIDENCE FEATURES

INTRODUCTION

The incidence features of G-induced loss of consciousness (G-LOC) clearly define its importance and the hazards to pilots of high performance aircraft. Simply, there is a high G-LOC occurrence rate—upwards of 25% of the pilots have probably experienced it. The total duration of time that the pilot is at least partially incapacitated is at least 30 sec, and complete recovery may be delayed by possibly several minutes. An aircraft traveling at 500 mph could cover 4 miles or lose 20,000 ft (6,096 m) altitude in a dive during those 30 sec (39,52).

The problem, therefore, centers on the episode of LOC that is unique to medicine. To a physician, losing consciousness is generally considered a symptom with underlying medical problems. Only during anesthesia is LOC premeditated and without major medical concern. Therefore, LOC is not generally the focus of research interest since it will disappear with the removal of the basic problem. On the other hand, LOC caused by the acceleration that occurs during aircraft maneuvers is basically a physiologic problem (not medical) and the G (or its cause) cannot be removed—it is inherent in flying high performance aircraft. In fact, if the history of military aviation is indicative of the future regarding acceleration capabilities of aircraft, G exposures of pilots will continue to increase in both level and duration.

G-LOC itself, therefore, becomes extremely important. Understanding the basis of LOC may allow us to alter its characteristics so as possibly to reduce its duration or even delay its onset and perhaps prevent its occurrence.

INCIDENCE OF G-LOC

The incidence of G-LOC has been determined in the United States, United Kingdom, Australia, The Netherlands, and Canada. The first in-depth survey was conducted for the U.S. Air Force (USAF) by Pluta (158) and reported in 1984 in Flying Safety. He received a 30% response from 6,400 anonymous questionnaires distributed to experienced pilots. Two hundred and twenty-seven incidents of G-LOC were reported, giving a 12 percent incidence rate. Most G-LOC occurred in high-G aircraft; e.g., the F-15 and F-4, but some also occurred in such low-G aircraft as the F-111 and OV-10. Clearly this survey identified a high incidence rate of G-LOC in the USAF and that G-LOC is not restricted to high-G aircraft. If the amnesia rate that occurs with G-LOC is factored into these survey results, probably 25 percent of all active-duty pilots who fly any high-G aircraft have experienced G-LOC.

The U.S. Navy (USN) survey showed a similar (compared with USAF) 14 percent G-LOC incidence rate (115). The rate of G-LOC relative to hours flown in a particular aircraft was calculated and is shown in Table 5-1. As in the USAF survey, the rate of G-LOC was directly related to the ability of the aircraft to develop high G. Similar data were reported in the Canadian, Netherlands, and Australian surveys. The Dutch surveyed all aircrew who attended centrifuge training at Soesterberg (187).

Table 5-1
Relative incidence of G-LOC per 10,000 USN flight hours (FH), (115).

Type Aircraft	TOTAL G-LOC	Total FH	G-LOC/ 10K(FH)
F/A-18	21	22,485	9.33
F-4	20	36,964	5.41
F-14	61	125,668	4.85
A-7	45	187,490	2.40
A-6	39	173,333	2.25
EA-6B	5	116,003	1.29

The G-LOC survey conducted by the Royal Air Force Institute of Aviation Medicine (RAF/IAM) at Farnborough, UK, revealed a higher rate of 19 percent G-LOC, with the majority occurring at 5 to 6 G predominantly in training aircraft not fitted with an anti-G system (161).

A comparison of the most frequent causes of G-LOC as found in three surveys is shown in Table 5-2. Rapid G onset, being unprepared, and performing a poor anti-G straining maneuver (AGSM) appear to be common problems. The first two can be argued as having the same cause.

Table 5-2
Most frequent stated causes for G-LOC in three surveys.

USAF	USN	RAF
1. Rapid G onset	Rapid G onset	Unprepared
2. Unprepared	No anti-G suit	No anti-G suit
3 G-hose disconnect	Poor AGSM	Rapid G onset

The occurrence rate of G-LOC in USAF undergraduate pilot training (UPT) program over a 42-month retrospective study was a total of 71 episodes or 1.7 per month (199). Sixty-three of these occurred during dual flights. The greatest number, 24, occurred between 3.1-4.0 G; however, 16 occurred within the 1 G lower range—some even at 2 G. The maximum was 6.5 G. Seventy-three percent blamed an improper AGSM as the reason—fatigue and an improper diet were also incriminating factors. The split-S (30%) and spin/dive recovery (23%) were the most common aerobatic maneuvers producing G-LOC.

PHYSIOLOGIC BASIS OF G-LOC

G-LOC occurs following a critical reduction of blood flow in the cerebrum due to increased acceleration—the higher intravascular hydrostatic pressures due to increased G are too great for the pumping action of the heart to overcome and raise blood to the level of the head (see Chapters 2 and 3). Without sufficient blood flow to the brain, oxygen supply to the brain tissue ceases and the brain cells rapidly use their small oxygen and energy reserves to maintain consciousness. This period of time without sufficient blood flow with consciousness remaining is called the latent G-LOC induction or functional (symptom-free) buffer period; it lasts approximately 5 sec (52,199). Its duration has been measured on the centrifuge during an extremely high G onset rate (20) and during blood flow occlusion at the neck (164).

Following this latent period, if the brain continues to be deprived of oxygen, G-LOC occurs. However, and quite surprisingly, the exact physiologic mechanism for G-LOC has yet to be identified. Although it is known that G-LOC is due to the anoxic changes that activate the potassium channel, the controlling substance is still unknown. Perhaps intracellular calcium, pH, or adenosine triphosphate (ATP) is that substance (103). Certainly knowing exactly how G-LOC occurs could identify targets of opportunity to interact with and possibly lengthen the latent period. A more rapid recovery from G-LOC might be achieved. Loss of consciousness that is not G induced, but caused by occluding blood flow at the neck, is only 1/3 the duration of G-LOC, suggesting that physiologic recovery from G-LOC can be more rapid (164).

A theoretical description of the neurophysiologic mechanism of G-LOC has been proposed (201). This theory has helped explain some of the physiologic and psychologic symptoms described later in this chapter (Tables 5-3 and 5-4).

PHYSIOLOGIC RESPONSES TO G-LOC

Cardiovascular Effects:

G-LOC does not appear to affect the cardiovascular system differently from those alterations normally expected with simple G stress. The maximum heart rate seen during the centrifuge exposures of 7 G averaged 134 bpm and occurred about 3 sec after the onset of G-LOC (41).

Cardiac rate or rhythm disturbances have not been observed to be associated with the occurrence of G-LOC (202). On the other hand, cardiac asystoles have extended the time of incapacitation (208).

Falling blood flow in the superficial temporal artery of subjects that may indicate a comparable loss (or significant reduction) of cerebral blood flow preceded light loss symptoms and G-LOC by 4 to 5 sec during rapid onset of G and 15 sec with slower G onset rates (109). More recently, using a transcranial Doppler technique suggests that G-LOC occurred with 25% relative blood flow remaining in the brain. Blood flow was reduced to zero 2 sec after G-LOC had occurred (197) (Fig. 5-1).

Noninvasive measures of cerebral oxidative state and blood volume using a near-infrared monitor (OMNI-4) found a significant overshoot in blood volume immediately following G-LOC, but absent in other runs when G-LOC had not occurred (94). Cerebral hyperemia following G-LOC has been confirmed using transcranial Doppler techniques (197). The extent of this increased blood flow is shown in Figure 5-1. This vascular hyperemic state is a common physiologic occurrence due to the immediately preceding tissue hypoxia.

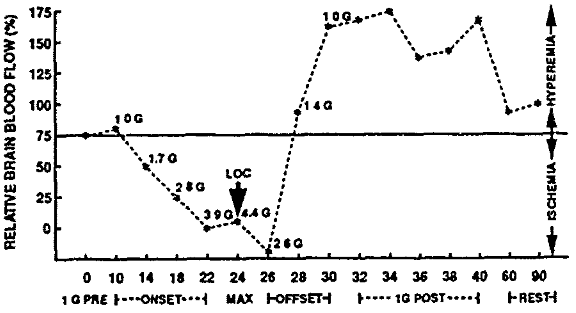


Fig. 5-1

Relative changes in cerebral blood flow in one subject resulting from G-LOC (197).

Central Nervous System Effects:

The electroencephalogram (EEG) during G-LOC was first recorded and reported by Franks et al in 1945 (79). Increased G without G-LOC found that alpha waves were replaced by high-frequency, low-amplitude waves. However, with the onset of G-LOC, progressively slower waves (8-2 per sec) of higher amplitude (50-200mV) appeared and remained until shortly before the return of consciousness. More recent studies have once again identified the occurrence of these slower theta and delta high-amplitude frequencies and a reduction of alpha and beta frequencies with G-LOC (138). The characteristics of the resting EEG could not be correlated with the occurrence or absence of convulsions in individuals during G-LOC (79).

MEDICAL ASPECTS OF G-LOC

Research involving G-LOC occasionally requires that subjects deliberately experience LOC. Since the exact physiologic basis for G-LOC is unknown, medical and ethical concerns have been raised regarding its deliberate induction (52). Therefore, attempts have been made to quantify the risk of this type of research. Although hundreds of G-LOC incidents have occurred since World War I (WW I) and no serious adverse nor detrimental effects have ever been reported, the possibility of some health risk cannot be ignored. However, a recent extensive review on the subject by Whinnery (202) concludes that "it is apparent that within a narrowly defined envelope unconsciousness research can be carried out safely in humans."

CHARACTERISTICS OF G-LOC

The first attempt at characterizing G-LOC was conducted by Stewart in an aircraft early in World War II (181). He photographed the entire G-LOC event and was, therefore, able to develop a timed sequence of events involving G-LOC (Fig. 5-2).

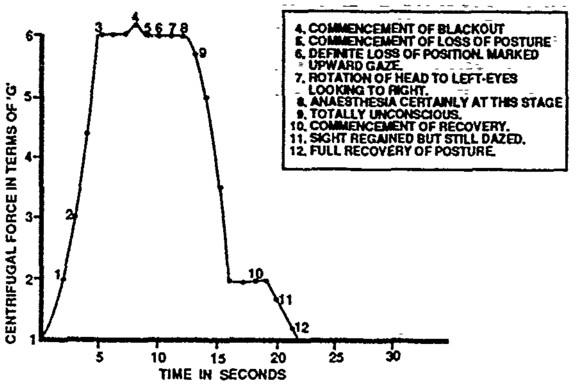


Fig. 5-2

Characterization of the observable events relating to G-LOC obtained from motion pictures taken during its occurrence in an aircraft (181).

Stewart (181) further characterized G-LOC by defining two types: (a) complete unconsciousness; and (b) impairment of consciousness. The former was more severe and involved: (1) alteration of posture and motor reactions; (2) loss of sensibility and muscle tone; (3) amnesia; and (4) increased subjective sensations. On the other hand, amnesia was absent following only impairment of consciousness. He also recognized that functional recovery from G-LOC required an additional 10 to 20 sec following physical recovery that had already lasted 12 sec. The psychological effect of lowered morale that followed G-LOC was also noted (181).

Period of Incapacitation:

The duration of G-LOC and its recovery has received considerable research attention over the last few years. The duration of G-LOC is generally defined as the period of time during which the subject loses muscular control, particularly as it affects posture and head positioning. This time of absolute incapacitation following unexpected G-LOC in subjects on the centrifuge is generally considered to be 15 to 17 sec (204.210).

Following absolute incapacitation, the subject is disoriented and generally unaware of the situation. This period is called relative incapacitation and begins at the end of absolute incapacitation and continues until the individual can voluntarily turn off a horn or light in response to an auditory or visual stimulus (Fig. 5-3). Relative incapacitation, also in unexpected G-LOC subjects, lasts for 15 sec also and its duration is independent of the nature of the arousing stimulus (204).

Arousal still leaves the subject with a performance decrement that is not resolved for approximately 2 min in subjects who deliberately lost consciousness on the centrifuge (109). We must assume, therefore, that although a pilot is probably capable of flying an aircraft 30 sec after a G-LOC, his ability to perform complex maneuvers, as might be required to recover from a difficult situation that had occurred during the G-LOC episode, must be considered in question. Interestingly, pilots recovering from G-LOC invariably "pull back on the stick" regardless of the orientation of the aircraft—a particularly dangerous maneuver if the aircraft had become inverted and lost altitude during the G-LOC.

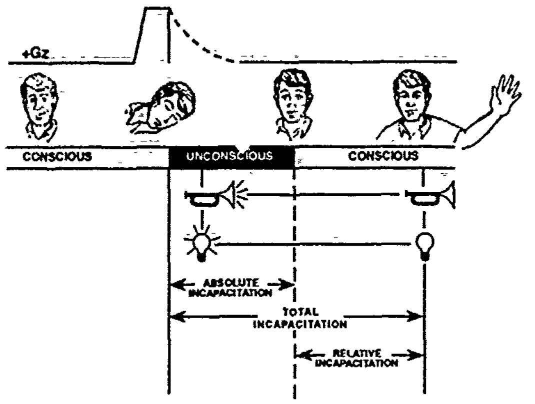


Fig. 5-3

Schematic of the incapacitation resulting G-LOC. A visual master caution light and auditory tone were used to determine the end of the relative incapacitation period (204).

The occurrence of convulsions by a subject during recovery after G-LOC has led to the definition of two types of G-LOC (203,204), with a convulsion indicating greater central nervous system (CNS) embarrassment. Convulsions were first described in detail in 1945 by Franks et al (79), who noted their presence in 52% of 230 test subjects. More recent data (204) have shown that 31% experienced convulsive-like flail movements during recovery from G-LOC.

Franks et al (79) described these convulsions as either slight or severe clonic seizures, with brief tonic episodes involving the extremities, face, neck, and trunk. They noted neck and trunk extension with arms extended in pronation and legs flexed. Usually violent jerks terminated the seizure in 2 to 5 sec.

Factors Affecting Duration of Incapacitation:

Factors affecting the incapacitation time usually involve differing conditions of the subjects, their responses during the G-LOC, and the rate of G onset (the environment). Subject responses to G-LOC have recently resulted in a form of classification found useful in describing this phenomenon (204). Episodes involving convulsions are classified as Type II G-LOC, having a longer mean absolute and relative incapacitation time of 37 sec than those classified as Type I G-LOC with an average 28 sec of relative and absolute incapacitation. As noted earlier in this chapter, Stewart (181) also classified G-LOC episodes into two groups—the group he considered having the more severe G-LOC symptoms exhibited amnesia.

The time of total incapacitation for non-aircrew is slightly longer by 1 to 2 sec than for experienced aircrew and UPT students (204,199). Deliberate (self-induced) G-LOC has a shorter relative incapacitation time of 3-4 sec compared to 12 to 15 sec for non-deliberate (not self-induced) or unexpected G-LOC episodes (203).

If a subject has experienced G-LOC previously, the relative incapacitation is shortened by an average of 8.5 sec. Accordingly, an intentional G-LOC incorporated into pilot centrifuge training could possibly reduce the duration of G-LOC that might occur later during flying (203). On the other hand, recurrent G-LOC episodes that are repeated two to four times over a span of a few minutes increase the incapacitation times (207).

Aerobically fit individuals appear to recover from G-LOC more slowly (109). A slow onset of G (0.1 G/sec) to G-LOC results in 40% longer incapacitation times compared with rapid G onset rates ($\geq$ 1 G/sec) (203).

Symptomatology:

Convulsive movements during G-LOC recovery have already been described. However, many other symptoms following G-LOC have been identified and are grouped as physiologic (Table 5-3) and psychologic (Table 5-4).

Table 5-3
Physiologic symptoms of post G-LOC (203).

1. Convulsive (flail) movements
2. Tingling: extremities, face
3. Impaired motor coordination
4. Unaware of G-LOC episode (commonly referred to in this chapter as amnesia)
5. Dream state/sense of falling asleep

Table 5-4
Psychologic symptoms of post G-LOC (203).

1. Confusion and disorientation
2. Suppression of G-LOC recognition (protection of self-esteem or self-image) - denial.
3. Unreliability
4. Altered judgment (lack of self-trust)
5. Embarrassment (ashamed of losing self-control)
6. Dissociation (prolonged)
7. Euphoria (false sense of well-being)
8. Anxiety
9. Fear (basal survival instinct)
10. Antagonism (towards centrifuge personnel and situation)
11. Give-up attitude

The most important of these symptoms are: (a) amnesia; (b) impaired motor coordination; (c) confusion and disorientation; and (d) denial. Amnesia and denial would reduce the number of reported G-LOC incidences, thereby reducing the apparent incidence rate and so artificially reducing the conception of the hazard. Since nearly 50% of the G-LOC individuals suffer from amnesia, the reported incidence of G-LOC may be only half the true figure. Retrograde amnesia, however, does not appear to be a feature (109). Impaired motor coordination and mental confusion extend the length of recovery and therefore increase the hazard of G-LOC.

Interestingly, the "give-up attitude" (Item 11 of Table 5-4) could become extremely important in a combat situation where an aggressive behavior has considerable importance.

AIRCRAFT RECOVERY FOLLOWING G-LOC

Since the duration of G-LOC is nearly half a minute and the aircraft is completely out of control for this time, various systems have been considered to control the aircraft to prevent a crash. These many proposed systems will not be reviewed here, but the general concept of auto recovery will be entertained.

These concepts can be grouped according to the type of method used to initiate the auto recovery mode. Three major methods exist: (a) physiologic monitoring of the pilot; (b) monitoring aircraft stick movement and/or the pilot's head position; and (c) using aircraft ground avoidance systems. The first two methods involve detecting LOC in the pilot while the third system, that does not involve the detection of G-LOC, would be useful in preventing accidents caused by G-LOC and those caused by spatial disorientation—a condition that causes many more accidents than G-LOC. For this reason, methods relying solely on the detection of loss of consciousness in pilots have not been intensely pursued. However, an aircraft recovery system that requires the detection of loss of consciousness in the pilot is shown in Figure 5-4.

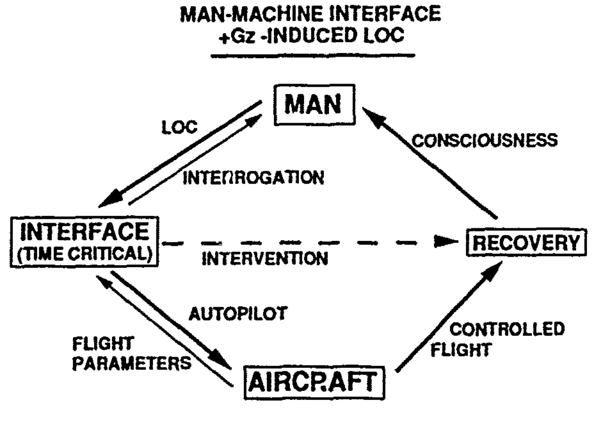


Fig. 5-4
Basic considerations in developing a G-LOC recovery system (206).

Various physiologic parameters that would be useful in detecting LOC and then initiating the autorecovery system of the aircraft are shown in Table 5-5.

Table 5-5
Potential physiologic monitoring of G-LOC (206).

Body system	Physiologic Parameter	Monitoring Technique
Brain	Electrical Activity	EEG, VER
	Blood Flow	Doppler
	Oxygen Saturation	Oximetery, NIL
	Blood Volume	NIL
	Metabolic State	NIL
Eye	Mechanical	Lid/Eye Movement
	Blood Flow	Retinal Reflectance
	Electrical Activity	EOG
Head	Mechanical	Position
Muscular	Mechanical	Pressure/Tension
	Neck	
	Face	
	Foot	
	Hand Grip	
	Jaw Clinch	
	Electrical Activity	EMG
Lungs	Respiration	Pressure/Flow Rate
		Thermal
Voice	Anti-G Straining Maneuver	Pattern Recognition

EEG = electroencephalography; VER = visual evoked response,
EOG = electrooculogram; NIL = near infrared laser monitoring of cerebral function,
EMG = electromyogram

Of perhaps greater interest is the concept of physiologic monitoring to detect some change preceding a G–LOC that could lead to its prevention. Recognizing early changes in the EEG (138), detecting a reduction in blood flow in the ear (ear opacity) or brain using the transcranial Doppler technique (197), or measuring changes in cerebral oxygenation with near-infrared technology (94) are candidates for such systems.

SUMMARY

G-induced loss of consciousness (G-LOC) occurs at least once in 12 to 19 percent of the pilots experienced in flying high performance aircraft. Since aircrew and experimental subjects are often unaware of having had a G-LOC episode because of amnesia-like symptoms, its incidence rate is probably much higher. Being unprepared for the high-G exposure—the failure to perform a proper anti-G straining maneuver (AGSM)—and the rapid onset of G are considered by the pilots to be the major causes of G-LOC. The incapacitation period of G-LOC can be divided into absolute and relative incapacitation. The former period, that is characterized by complete loss of muscular control of posture and head positioning, lasts 15 to 17 sec. The latter, also lasting about 15 sec, is the period of subject disorientation and state of unawareness. Arousal, however, still leaves the subject with some performance decrement for at least another 2 min. If convulsions occur with G-LOC, it is called a Type II G-LOC with incapacitation periods of 37 sec average, whereas Type I G-LOC without convulsions lasts 28 sec on the average. The symptoms of G-LOC are many, but the most important are convulsions, impaired motor coordination, amnesia, confusion and disorientation, and denial (that it occurred). An auto recovery system for aircraft designed to prevent a crash while the pilot is experiencing G-LOC is proposed with some caution regarding its potential effectiveness.

BILAN DE L'INFLUENCE DES PERTES DE CONNAISSANCE SOUS FACTEUR DE CHARGE.

Au cours de leur carrière, 12 à 19 pour cent des pilotes ont eu au moins une perte de connaissance liée aux accélérations (G-LOC, G induced Loss of Consciousness). Ce taux est probablement encore plus élevé puisqu'on a remarqué chez des sujets d'expérimentation et chez des pilotes qu'ils n'ont aucun souvenir de cet épisode. Les pilotes considèrent que la survenue des pertes de connaissance est liée à un défaut de préparation à une accélération élevée et rapidement installée. En fait, ce défaut consiste en la mauvaise exécution de la manoeuvre anti-G. La perte de connaissance sous accélérations peut être décomposée en deux périodes: une période d'incapacité absolue et une autre d'incapacité relative. La première est caractérisée par la perte du contrôle musculaire postural ainsi que du positionnement de la tête. Sa durée est d'environ 15 à 17 secondes. La seconde période, d'une durée d'une quinzaine de secondes, est caractérisée par un état de désorientation et d'inconscience partielle du sujet. A l'éveil, les performances du sujet restent dégradées pendant au moins deux minutes. Si la perte de connaissance est accompagnée de convulsions, il s'agit d'une perte de connaissance de type II. Sa durée moyenne est alors de 37 secondes. S'il n'y a pas de convulsions, il s'agit d'une perte de connaissance de type I dont la durée moyenne est de 28 secondes. Parmi les nombreux symptômes observés au cours des pertes de connaissance, on retiendra les principaux: convulsions, détérioration de la coordination motrice, amnésie, confusion, désorientation et négation (de ce qui vient d'arriver). Un système automatique de sauvegarde de l'avion destiné à éviter le crash en cas de perte de connaissance est proposé avec toutefois certaines réserves concernant son efficacité potentielle.

CHAPTER 6
NATO CENTRIFUGE FACILITIES

INTRODUCTION

The high maneuverability and performance of the new generation of fighter aircraft and the loss of a number of these aircraft to G-induced loss of consciousness (G-LOC), have inspired a renewed interest in human centrifuges. Until recently every human centrifuge in the North Atlantic Treaty Organization (NATO) nations and the other countries of the free world was quite old, most were built in the 1950s or 1960s. Without exception, these centrifuges were built for research, and most had very low performance by today's standards. Within the last few years nearly every nation that owns or plans to acquire one of the new generation fighters has investigated either upgrading the performance of their existing centrifuge or building a new centrifuge facility for training their pilots. This chapter offers some definitions, discusses some of the desirable attributes of such pilot training centrifuges, and describes the existing centrifuge facilities in the NATO countries.

Since this chapter discusses and describes human centrifuges, some basic configurational assumptions and definitions about such devices must be made and will be used throughout this chapter. In most centrifuge designs a structure is rotated about some point by some powered drive mechanism. This structure will be called the centrifuge "arm". Its motion about the central point, called the "base", will be designated "centrifuge revolution". Mounted at the end of the arm is some type of platform, fixture, or housing which contains the trainee or test subject. This device will be called the "gondola".

DEFINITIONS

The orthogonal axes of the gondola, with the origin at the center of the gondola, will be defined as follows:

1. The longitudinal axis extends fore and aft.

2. The vertical axis extends up and down.

3. The lateral axis extends left and right.

Angular motion of the gondola about these axes will be designated "rotation" and will be defined as follows:

1. Pitch, rotations of the gondola about its lateral axis. Pitch will be designated (+) (pitch nose up) and (-) (pitch nose down).

2. Roll, rotation of the gondola about its longitudinal axis. Roll will be designated (+) (clockwise) or (-) (counter clockwise) facing the direction of centrifuge revolution.

3. Yaw, rotation of the gondola about its vertical axis. Yaw will be designated (+) (nose right) and (-) (nose left) facing the direction of centrifuge revolution.

Linear acceleration reaction force vector directions (G_X, G_Y, and G_Z) within the gondola were defined in Chapter 2.

In specifying the requirements for a new or upgraded centrifuge facility, three factors must be taken into account. First, the desired performance of the machine must be defined. If the system is an old centrifuge being upgraded, some compromises may be necessary since the design of the structure and drive systems of most of these machines never anticipated today's G_Z and onset rate requirements. Second, the design must be carefully accomplished and reviewed to assure the maximum level of safety for the trainee and operators. Safety must not be compromised and must be the driving factor in design considerations. Third, design features and equipment required for the particular installation must be decided and defined. In some cases the centrifuge facility is to be used for both research and training and much more data acquisition and monitoring capability will be required. If the system is to be used only for pilot training a much simpler and less expensive system will suffice. There is no universal agreement as to what features or equipment a training centrifuge should have. While some features are absolutely mandatory for adequate pilot training (e.g. an Anti-G valve system), others are a matter of opinion (e.g. pitch control of the gondola).

PERFORMANCE

In defining the performance of centrifuges, two parameters are usually specified: maximum G_Z and onset rate. Chapter 2 gives a detailed description of the physics involved with the production of G forces in a centrifuge and defines G_Z. Onset rate, however, requires more explanation and definition. Onset rate is usually expressed as a simple number of G_Z per second - e.g., 6 G_Z/sec. This concept is relatively simple, as a rate of change of G force within the gondola with respect to time. It is also apparent that this rate of change is accomplished by changing the angular velocity of the arm at some rate. What is not as apparent is that onset rate, expressed as a simple number of G per second, is an average angular acceleration and a centrifuge system simply does not respond in that way. The torque required of the drive system to accelerate the arm at a given rate is much greater at lower angular velocities, and since it is not desirable that the control system allow large overshoots of the target G level, it is necessary that the onset rate be reduced as the target level is approached. Further, experience has shown that it is not desirable for the initial onset rate to be too high because the trainee may be distracted by the "bump" in $+G_X$. The result of these factors is that the actual trace of G_Z vs time is an "S" shaped curve. It is well then, when defining the onset rate of a proposed system, to specify first an average onset rate by allowing a certain amount of time for the system to increase G_Z from one level to another. Then specify the maximum onset rate allowable below a certain G_Z level to minimize the "bump", the highest onset rate allowable in the G_Z vs time profile, and finally the amount of overshoot of the target G_Z level that will be tolerated. To limit the initial high forces on the drive system, it is usual that the centrifuge be slowly accelerated to some low G_Z level, called "base G_Z", before the initiation of high onset. This level should be kept as low as practical and should not be higher than 1.4 G_Z. It is recommended that, for a training centrifuge, the onset rate be at least 3.5 G_Z per second from base G_Z to 9 G_Z.

Other control system performance requirements may be specified, such as the ability to maintain a set G_Z level within certain limits, to control a minimum onset rate with a required accuracy, or to control offset rate (reduction of G force with time or negative onset rate). Other system performance requirements may also be specified, including instrumentation accuracy, equipment specifications, number of operations per day, expected system lifetime, or repair and maintenance schedule.

SYSTEM SAFETY

As was stated earlier, system safety is a prime consideration. With the high onset characteristics of a modern training centrifuge the control system must be "backed up" by automatic devices which will limit G_Z in the event of control system failure. If the centrifuge is computer controlled, at least one independent electrical and one independent mechanical backup to limit the peak G_Z attainable are recommended. An electrical / computer interlock system which will preclude centrifuge operation unless all system prerequisites are satisfied should be in the system design. It should include a check of computer parameters, and facility requirements such as door and hatch security. An adequate design safety factor of not less than 1.5 should be included in all mechanical and structural specifications. Emergency centrifuge stopping modes and quick trainee access should also be considered. Periodic inspections and tests should be conducted to assure the proper operation of emergency equipment, and drills of operations and medical personnel should be conducted to maintain proficiency in emergency procedures. A thorough system and operations safety review, including a Failure Modes and Effects Analysis (FMEA), should be conducted of all new or upgraded designs.

DESIGN FEATURES

One of the first decisions that must be made as to what characteristics or features a new or upgraded centrifuge must have is the method of gondola angular control. Since the G_Z experienced by the trainee is the vector sum of the G_R (radial G produced by centripetal force) and the earth's gravitational field, the gondola alignment with the changing G_Z vector must be maintained. This is usually accomplished in one of two ways. The simplest and most ordinary method is called "passive or inertial" control. The gondola is mounted in bearings at both ends so that it is free to rotate in the roll axis. The center of gravity of the gondola must be kept well below the roll axis so that the force acting through the center of gravity will maintain the alignment with the G_Z vector. It is usually necessary that some form of damping of the roll axis be provided to keep gondola oscillations at an acceptable level during high G onset. Another much more complex and expensive method used in some centrifuge systems is called "active or computer" control. This method involves the use of a computer to solve the vector equations and the use of drive motors to align the gondola with the G_Z vector. In some cases the pitch and even the yaw axes are computer controlled. In these cases the gondola must be mounted in separate gimbal rings and have a separate drive system for each axis. The advantage of controlling the pitch axis is that the X direction forces experienced in onset and offset can be resolved into the Z direction by proper solution of the vector equations, and the effective G_Z onset rate of the system can be increased by including the X vector accelerations. Since, when only the roll axis is active, the trainee will perceive the X acceleration during G_Z onset, there is also some advantage to controlling the pitch axis and reducing this disorientating effect. The cost and complexity of an active control system are obvious. The added mass of the gimbal and drive systems required for active gimbal control also greatly increases the inertia of the arm and therefore increases the power and size requirements of the drive system which, in turn also increases system cost and complexity. Because of the initial cost in building such a system and the increased maintenance required, it is doubtful that an active gimbal control system is justified for a purely training centrifuge.

For new systems or modifications which require a new arm, the length of the arm must be considered. The radius of an aircraft pulling G in a turn is many times the radius of the largest centrifuge arm. Coriolis forces, although they exist in the aircraft turn, are not noticed by the pilot because of this large turning radius. This is not the case in a training centrifuge. Even in centrifuges with arms as long as 15 m the disorientating effects of Coriolis force cause the sensation of tumbling during onset or offset and may cause dizziness or nausea in the trainee. Unfortunately the Coriolis effect is not reduced effectively by increasing the centrifuge arm within practical limits. For example extending the length of the arm from 6 m to 9 m would result in a relative reduction in Coriolis effect of only 18 %. A more important consideration in defining the length of a centrifuge arm is that inertia increases by the square of the distance from the center of revolution and the drive train requirements are greatly increased by longer arm lengths. For instance in the example given above the increase in arm length from 6 m to 9 m would increase the moment of inertia by a factor of 2.25 and the torque requirements of the drive motor by the same factor. Most human centrifuges have arm lengths between 6 and 10 m and have proven satisfactory for most purposes.

Another area which must be included in the specification of a training centrifuge, is whether to allow for control of the G_Z level and possibly the onset rate from inside the gondola. Usually called "closed loop, man - in - loop, or subject control," this system is usually implemented by use of an aircraft type control stick, or side arm controller. This feature requires that some type of computer control of the centrifuge system be used and that a computer-driven tracking task display also be provided. This display usually features a horizon line that is banked to represent a turn equivalent to the G_z being generated and some sort of target. The trainee must "pull" varying G_z levels to track this target. Target shooting and scoring may also be included. Experience has shown that closed loop control greatly enhances G training and is highly desirable for any centrifuge used for pilot training.

The gondola should be equipped with a representative ejection seat or mock-up which can be adjusted to represent the correct back angle of the seat in the aircraft that the trainee is currently flying. The control stick or side arm controller, rudder pedals, Anti-G valve and pressure supply system should also approximate the configuration of that aircraft. A NATO standard light bar should also be installed for estimation of peripheral vision loss (See Chapter 3). Many centrifuge training protocols require a run with the trainee seated in a "check 6" (head turned to the rear) position. This training can be enhanced by the inclusion of a single digit display located at the rear of the gondola, on which the number can be changed from the control room. If the trainee turns his head until he can read and report the number, the correct position for the check 6 run can be assured.

A Closed Circuit Television (CCTV) system for monitoring the trainee during centrifuge runs is required and a video cassette recording is of benefit in debriefing trainees.

The instrumentation requirements for a centrifuge used strictly for training are quite simple. A system for collecting and displaying electrocardiogram and heart rate is needed for some training protocols. The G_z level and pressure in the G-Suit should also be recorded. The G-Suit pressure trace provides an indication of Anti-G Straining Maneuver (AGSM) timing and strength and is of value in briefing and instructing trainees on the proper performance of the AGSM.

NATO CENTRIFUGE DESCRIPTIONS

CANADA

HISTORY

The centrifuge at the Defence and Civil Institute of Environmental Medicine (DCIEM), Toronto, Ontario, Canada, was brought into service in 1988. This machine was rebuilt beginning in 1982 by EMRO Engineering Co., who designed and built a new pedestal, arm, and gondola. The motor, gearbox, drive shaft, computer control system, instrumentation, and gondola interior components were provided by DCIEM, some of which were from an earlier human centrifuge. This centrifuge is used for research and aircrew training.

SYSTEM PERFORMANCE

This centrifuge system is capable of a maximum continuous level of 15 G_z and can provide an average onset rate of 1.5 G_z per second from a baseline of 1.4 G_z. This system will provide full performance with a maximum payload of 320 kg.

SYSTEM DESCRIPTION

The length of the arm is 6.1 m from the center of revolution to the axis of rotation of the gondola. The gondola is rectangular with a rounded top in shape, is constructed of an aluminum alloy, and has an empty weight of approximately 180 kg. It is of semi-monocoque design and riveted construction. The gondola dimensions are 1.83 m long by 0.9 m wide by 2.1 m high for an internal volume of approximately 3.25 m^3. The gondola is passively coupled to the G_z vector and pivots on self-aligning trunnion bearings. The interior of the gondola is fitted with a typical fighter aircraft ejection seat. A curved light bar is mounted at test subject eye level and can be adjusted to maintain a standard distance from the subject. A panel is provided for mounting any type of Anti-G valve. The subject is monitored during runs by a CCTV camera mounted in the gondola. The gondola also houses various equipment racks for mounting amplifiers, instrumentation, and experiment support equipment. Connection and amplification facilities are provided by a specially designed and manufactured slip ring assembly designed for DCIEM by the Nova Scotia Research Foundation in Dartmouth. This assembly is made up of 150 instrumentation quality rings, a fiber-optic rotary joint, three oxygen compatible fluid rotary joints, 75 power and control rings, 5 coaxial rings for CCTV, and one shaft encoder with 10 bit resolution.

The emergency mechanical brake consists of a band brake system which is hydraulically actuated and bears against a brake drum located on the drive shaft between the motor and the gearbox. It is selectable from the control consoles in the event of an emergency which precludes the use of normal electrical braking.

The drive train of the centrifuge consists of a single 150 kW, air cooled, DC electric motor. This motor is located in a sub pit below the main centrifuge room. This pit also houses the main drive shaft, the gearbox, safety clutch, and the hydraulic brake system.

Control of the centrifuge acceleration profiles is accomplished using a DEC 11-23 computer system. System status, G_z profile selection and display, interlock status, system parameters, and real time run data are presented on computer console displays in the control room. All runs are accomplished under the control of the computer, and no closed loop control is available.

The Control Room is located on the floor above the centrifuge pit and contains the required equipment for system operation, research data acquisition, recording and display and medical monitoring. Subject CCTV is provided for the medical monitor and the investigator with G_Z, peak G_Z, heart rate and date displayed on the screen. Three channel EKG is also provided for the medical monitor. Research data is presented on an eight-channel Gould recorder which displays the analog conversion of digitized data from the computer. A gas control panel is also located in the Control Room which controls the flow of up to three separate gases to the gondola through a series of gas slip rings. One of these circuits usually provides compressed air at 690 kPa pressure for Anti-G suit actuation.

FRANCE

HISTORY

The French Air Force centrifuge is located at the Laboratoire de Médecine Aérospatiale, Brétigny, France. This machine was designed and built by Latécoère and was brought into service in 1956. It is used for medical evaluation, physiologic and medical research and equipment test and evaluation.

SYSTEM PERFORMANCE

This centrifuge system primarily uses 3 different gondolas and has different performance specifications with each. With the two gondolas used for human studies a maximum continuous level of 15 G_Z can be attained with an average onset rate of 1 G_Z per second. With the equipment gondola a maximum level of 40 G_Z can be attained with an average onset rate of 7 G_Z per second.

SYSTEM DESCRIPTION

The length of the arm is 6 m from the center of revolution to the axis of rotation of the gondola. Counterweights are located at the opposite end of the arm from the gondola mounted inside an enclosed housing which surrounds the drive spindle. The arm and gondolas are constructed primarily of steel. The total weight of the rotating assembly with the equipment gondola is approximately 8,700 kg and with the human gondola, 10,500 kg. The arm and yoke are of semi-monocoque design. The human gondola is cylindrical, 3 m in diameter, and is mounted in the yoke at points across its diameter as opposed to its longitudinal axis. The gondola is passively coupled to the G_Z vector and pivots on trunnion bearings mounted on the centerline at each end or can be fixed at any desired angle of roll for G_Y studies. Damping of the gondola rotation is provided by a hydraulic actuator. The interior of one of the gondolas is fitted with a Martin Baker MK 10 ejection seat which can be set at any desired back angle. A curved light bar with LEDs at each 10 degrees is also installed. This light bar can be controlled by the subject using a joystick for precise measurement of peripheral light loss. A panel is provided for mounting any type of Anti-G valve at approximately the heart level, and O_2 at up to 2000 kPa is provided for a pressure source. The subject is monitored during runs by a CCTV camera. No environmental conditioning is provided in the gondola. The gondola also houses equipment racks for mounting instrumentation and experiment support equipment. Connections are provided for approximately 100 slip rings for electrical power and experiment instrumentation use.

The mechanical brake consists of 2 separate pneumatically actuated disc systems which have adjustable pressure valves to control the centrifuge descent rate.

The drive train of the centrifuge consists of a 56 kW direct drive DC electric motor which can maintain the centrifuge at a constant G_Z level or accelerate the system at onset rates of up to 0.3 G_Z per second. For high onset operations a pneumatically actuated piston (catapult) which is connected to a cable wrapped around a spool on the main centrifuge drive shaft is utilized. The onset rate is controlled by adjusting the pressure applied to the piston. This system is limited to 1 G_Z per second for human runs but can provide up to 7 G_Z per second for equipment tests.

Control of the centrifuge is accomplished manually by two operators, one for control of the electric motor and the other for control of the catapult system, from control panels located on a wall above the centrifuge level. The subject is monitored from the Medical Observation Area on CCTV and medical or physiologic signals are recorded on a 12-channel Gould pen recorder.

Data recording is available in both analog and digital format with analog to digital conversion and some real time analysis being accomplished on a PDP 11/70 laboratory computer. Analog signals are recorded on a 12-channel paper chart recorder.

FEDERAL REPUBLIC OF GERMANY

HISTORY

The German Air Force Centrifuge is located at the Air Force Institute of Aerospace Medicine, Fürstenfeldbruck, West Germany. This machine was completed, using a previously existing motor and drive train, in 1980 by the West German firm of Messerschmitt, Bölkow and Blohm. This facility is used for both physiologic and medical research and for pilot training.

SYSTEM PERFORMANCE

This system is capable of a maximum level of 10 G_Z and provides a rate of onset of 3 G_Z per second. The system is designed to provide full performance with a payload of 200 kg in the gondola. Both pitch and roll of the gondola are computer controlled for optimum alignment of the Z axis with the resultant acceleration vector.

SYSTEM DESCRIPTION

The length of the centrifuge arm is 10 m, from the center of revolution to the attachment of the center gimbal to the gondola. The arm is of a rectangular truss design and is constructed of tubular steel members.

The gondola, which is small and is of very light construction, is nested in a two gimbal system with the roll axis being the inner of the two. The position of the gondola is controlled by two electric motors, one for each axis, which drive through clutches for safety considerations. The position and rate of rotation can be controlled by computer for accurate alignment with the G_z vector or can be controlled or fixed at any desired angle for "off axis" operations. The ejection seat is mounted to a hatch in the bottom of the gondola such that when this hatch is opened, the seat is lowered allowing quick and easy emergency access to the subject. Another benefit of this system is that the subject is tilted back, when this hatch is opened, so that the head is lower than the feet which facilitates restoration of blood circulation to the head. The basic equipment mounted in the gondola consists of an ejection seat, a control stick which can control gondola pitch motion for flight simulation and a switch for the subject actuated brake, a joystick and monitor for target tracking and information display, a CCTV camera and audio communications system, an oxygen system, and a compressed air supply for Anti-G suit inflation. The gondola can be easily removed and replaced by a test platform which is used for testing materials and equipment.

The centrifuge is driven by a 265 kW electric motor through a 90-degree gear box.

The centrifuge system is under the control of a process control computer, both for G_z profile generation and gondola positioning. This computer system is active whether the centrifuge system is under the control of an operator, is under the control of the subject, or is in programmed automatic control.

The Control Room houses a series of consoles for centrifuge control and medical monitoring of the subject. The operator's console provides a computer terminal for communication with the control computer and the necessary displays for monitoring system performance. CCTV of the subject and a medical strip chart provide information to the medical monitor on subject condition and experimental data.

A data acquisition and transmission system is located in the gondola with terminals at the disposal of the centrifuge user. This system can be multiplexed for digital serial data transfer or can be configured for simplex data transmission.

THE NETHERLANDS

HISTORY

The Dutch centrifuge is located at the National Aerospace Medical Center, Soesterberg, The Netherlands. This system was designed and rebuilt starting in 1979 by HOLEC Co. and the Dutch Aerospace Laboratory and was operational in August of 1983. It is used for aircrew training, physiologic and medical research, and equipment test and evaluation.

SYSTEM PERFORMANCE

This centrifuge is capable of a maximum continuous level of 23.5 G_z that can be attained with an average onset rate of 3.5 G_z per second starting at a base of 1.04 G_z. This system will provide full performance with a maximum payload of 175 kg in the gondola.

SYSTEM DESCRIPTION

The length of the arm is 4.0 m from the center of revolution to the axis of rotation of the gondola. Counterweights are located at the opposite end of the arm from the gondola. The arm is constructed of stainless steel. The gondola structure is an aluminum skin on a steel frame which weighs approximately 250 kg. The gondola is basically rectangular in shape and is small compared to other NATO centrifuges, being approximately 2 m in length and 0.5 m wide. It is passively coupled to the G_z vector and pivots on trunnion bearings mounted on the centerline at each end. Damping of the gondola rotation is provided by a hydraulic actuator. The interior of the gondola is fitted with a mock-up ACES II ejection seat which can be set at any desired back angle up to 30 degrees and can be electrically adjusted fore and aft and in height. A light bar with a central red light and outer green lights is mounted at subject eye level and can be adjusted to maintain a standard distance from the subject. A computer-generated "outside world" with a horizon, sky, and landscape display is projected on a large monitor directly in front of the subject. A head-up display with an aiming reticle and a target designator gives the pilot information to follow a computer generated picture of a "target" airplane. Closed loop control is accomplished by the trainee using an F-16 type side stick with trim and trigger buttons. A go - no go switch is located on the simulated throttle quadrant. Target control, centrifuge control and display generation is accomplished by using two interconnected computer systems, a Silicon Graphics "IRIS" computer system and a VME bus microcomputer system. An Alar High Flow Anti-G valve is used and source pressure is provided by a high pressure bottle mounted on the arm. The subject is monitored during runs by a low light level, auto focus CCTV monitoring and recording system. Voice communications with the subject are maintained by a "hot mike" system. Ventilation is provided in the gondola during operations by two electric fans. The gondola also houses equipment racks for mounting instrumentation and experiment support equipment. Connections are provided for each of 48 gold and 24 silver slip rings for experiment instrumentation use.

The drive train of the centrifuge consists of a 170 kW direct drive DC electric motor and gear box system.

The emergency mechanical brake consists of a band brake system which is hydraulically actuated and bears against a brake drum located on the drive shaft between the motor and the gearbox. It is selectable from the control console in the event of an emergency which precludes the use of the normal electrical brake.

Control of the centrifuge is accomplished by an operations team consisting of five operators: a Supervisor, with overall responsibility for the training, safety and instruction; a Medical Supervisor, responsible for medical guidance; a Monitoring Systems Operator, responsible for readying the trainee and the gondola for the run; and a Safety Equipment Controller, responsible for assuring the safety and readiness of the trainee's personal equipment and instrumentation. Three modes of centrifuge control are available: closed loop from the gondola, computer control, or manual operator control.

Medical and physiologic signals are stored in a computer, and selected channels are also recorded on a paper strip chart recorder for immediate analysis. Video signals are recorded and used for post-training debriefing and analysis.

TURKEY

The Turkish Air Force Training centrifuge was brought into service in early 1990 at their new aeromedical center at Eskisehir, Turkey. This facility was built by Environmental Tectonics Corp. (ETC) of Philadelphia, PA and is essentially identical (with small specification differences) to the centrifuge at Holloman AFB, USA which is described in detail later in this chapter.

UNITED KINGDOM

HISTORY

The centrifuge at the Royal Air Force Institute of Aviation Medicine, (RAF/IAM), Farnborough, Hampshire, United Kingdom, was constructed between 1951 and 1954 by GEC Ltd as prime contractor and was brought into service in 1955. It is used for both aircrew training and research operations.

SYSTEM PERFORMANCE

This centrifuge system is capable of a maximum continuous level of 30 G_z and can provide a maximum onset rate of 2 G_z per second from rest.

SYSTEM DESCRIPTION

The length of the arm from the center of revolution to the axis of rotation of each of two gondolas mounted at either end of the arm is 9.14 m. A materials or equipment test fixture, called an "end barrier", can be mounted at either end of the arm in place of the gondola. The arm is a 290 cm square cross-sectional tubular truss structure constructed of 7.6 cm diameter steel tubing. The aluminum alloy gondolas are mounted to the arm in fore and aft trunnions and are inertially coupled to the G_z vector. They have a transparent canopy at the top to allow viewing the subject from the center of the arm and are structurally identical with exterior measurements of 122 cm wide by 244 cm long by 244 cm high. Each gondola can carry a maximum payload of 132 kg at 5 G_z or 45 kg at 10 G_z. Each gondola is equipped with a hydraulic damping system to limit oscillation during rapid changes in G_z. Both gondolas are available for human use (for example; for parallel $+G_z$ and $+G_x$ studies) or one may be used as a counterweight. The entire rotating mass (45,714 kg) is supported by the drive motor bearings, balance of the system is critical and the gondolas are removed from the arm and weighed to assure proper balance after each major test setup. Access to the gondolas is through the arm side. The arm is mounted at the center on a 12,218 kg flywheel which also acts as a brake drum for the hydraulic brake system. This flywheel is directly fastened to a vertically mounted 1000 kW DC drive motor. Times, G_z level, and onset and offset rates are all controlled by the selection and installation of different cams in the Cam Drive Profile Generator located in the Control Room. Both regenerative and mechanical (hydraulic) braking are used. Voice communication with the subject in the gondola is possible from a Central Observer position at the center of the arm or, via the Observer, from the Control and Recording Rooms. CCTV coverage of the subject is also available at both of these locations. A set of slip rings is located below the motor which transmits electrical power to the gondola. A set of 60 slip rings is housed in a separate shielded room for medical monitoring and a set of 128 unshielded slip rings is available for signal transmission and data collection in the Control Room. A set of gas slip rings provides breathing gases, vacuum, and Anti-G suit air to the gondola and permits the continuous analysis of expended gases using a respiratory mass spectrometer.

A complete variety of medical and physiologic monitoring devices and instrumentation is available for research. Data can be taken both at the Control Room and at the Medical Monitoring Room.

UNITED STATES

NASA CENTRIFUGE

HISTORY

The NASA Centrifuge located at Ames Research Center, Moffett Field, California, USA, was built in 1966 to subject experimental research packages to the Biosatellite launch and recovery acceleration profiles. The centrifuge is currently being used to support research related to the U.S. space program. Use of this centrifuge is available to outside agencies for a fee.

SYSTEM PERFORMANCE

The NASA centrifuge can provide up to 20 G_z to a payload of up to 550 kg or (7300 G kg) at either end of the arm. It is man-rated for operation to 12.5 G_z. The onset rate is 1 G_z per second from 1 to 12 G_z and 0.5 G_z per second from 12 to 16 G_z. Braking time under power is 25 seconds from 20 G_z. Braking after automatic cutoff by the control system (due to over speed, over voltage/amperage, exceeding G_z onset rate, etc.) is with dynamic braking and relies on the torque of the motor acting as a generator, plus the inertia and friction within the drive and gearing systems. Stopping time from 20 G_Z in this mode is 3 minutes.

SYSTEM DESCRIPTION

The arm is an open rectangular truss structure, 17.68 m long, supported by a vertical shaft at the center. Gondolas, 2.1 m high, 1.8 m wide, and 2.3 m deep, are mounted at each end of the arm. Radial distance to the center of each gondola is 7.62 m.

The centrifuge design includes optional provisions for mounting animal or instrument experiments on a swinging basket in one gondola to provide a resultant acceleration vector normal to the basket. A modified aircraft ejection seat is installed in the other gondola for tests with human subjects. This seat is free to rotate and provides a normal (head to foot - subject facing out) acceleration vector for research into human capability studies. Unlimited possibilities exist for other arrangements for human, animal, or instrumentation package experimental research within the design constraints of the NASA Ames Centrifuge facility. Among modifications that are in development is a treadmill installation to evaluate the effects of exercise during altered gravity conditions.

Drive torque is applied to the center shaft by a 400 kW DC drive motor through a gear box. DC power for the drive motor is provided by a 250 kW, 600 volt DC generator driven by a 533 kW, 440 volt, 3 phase AC motor. The control system for the DC drive motor includes provisions for both manual control and program control [illegible]ation profiles. The field of the DC generator is controlled via servo amplifiers from either the manual control at the control console, or through a preprogrammed profile from a DATA TRAK controller.

A total of 47 control and 56 instrumentation slip rings are provided for experiments. These slip rings may be installed at either or both ends of the centrifuge arm.

Operating controls, instrumentation displays, and data acquisition equipment are located in the control room area adjacent to the centrifuge arm.

USAF DYNAMIC ENVIRONMENT SIMULATOR

HISTORY

The USAF Dynamic Environment Simulator (DES) is a three-axis centrifuge located at Wright-Patterson AFB, Ohio, USA. The DES is operated by the Acceleration Effects Branch (BBS), Biodynamics and Bioengineering Division, Armstrong Aerospace Medical Research Laboratory (AAMRL). This facility was designed and constructed by Franklin Institute of Philadelphia, Pa. in the mid 1960s and has been in service since 1969. The DES is used to support research involving performance in sustained acceleration environments, physiology, and spatial disorientation and has been used for aircrew training.

SYSTEM PERFORMANCE

This system is capable of a maximum sustained level of 20 G at an average onset rate of 1 G per second. The three-axis feature of the DES allows the generation of complex G fields including $\pm G_X$, $\pm G_Y$, and $\pm G_Z$. In addition to the main arm rotation there is an outer gimbal (the fork) and an inner gimbal (the cab or gondola). The maximum payload of the gondola floor is 227 kg at 12 G. Additional payload may also be mounted inside the gondola on the main support structure. An aft-mounted experiment platform is provided to support experiments involving animals and equipment. The maximum payload of the aft-mounted platform is 181 kg.

SYSTEM DESCRIPTION

The length of the main arm is 5.8 m from the center of revolution to the center of the axes of rotation of the gondola. The center of the aft-mounted experiment platform is 6.3 m from the center of revolution of the arm. The aft-mounted platform may be locked at any desired angle or allowed to swing free to the normal vector. The rotating structure weighs 162,000 kg and supports the fork and gondola. The arm is supported by a hydrostatic bearing system which provides a low friction suspension of the rotating structure. The arm is driven by three 82 kW DC motors connected by pinion gears to a common bull gear. The three drive motors are rated at 300% overload for short durations. The maximum velocity of the arm is 56 rpm (6.12 rad/s). The outer gimbal, or fork, rotates about a horizontal axis and is capable of rotational speeds of ± 30 rpm (3.14 rad/s) with a maximum acceleration of 2.5 rad/s/s. The fork is driven by a directly coupled 67 kW DC motor controlled by a servo control system. The inner gimbal rotates about an axis perpendicular to the fork axis and is capable of rotational speeds of ± 30 rpm (3.14 rad/s) with a maximum acceleration of 5.0 rad/s/s. The gondola is driven by four fixed displacement hydraulic motors and is controlled by a servo control system. The interior diameter of the gondola is 3.0 m. The interior of the gondola may be configured with any of several available aircraft seats. The seats may be oriented in line with respect to the center of rotation or tangential to the direction of rotation of the arm, depending on the requirements of the experiment. Several types of seats are available, ranging from standard USAF systems (i.e., ACES II) to custom-designed variable tilt seats. Additional equipment available includes video displays, rudder pedals, force or displacement control sticks, instrument panel mock-ups, CCTV cameras, still cameras, voice communications system, instrumentation amplifiers and a light bar. Thirty-two pairs of shielded twisted signal wires, 24 pairs of #16 AWG power wires, and 4 coaxial cables are available for use within the gondola. Primary power of 115 VAC 60 Hz, 220 VAC 60 Hz, 115 VAC 400 Hz, and 28 VDC are also available. Electrical signals from the gondola are routed through three sets (gondola, fork, and arm) of high quality slip rings to the medical monitor room. Signals from the aft-mounted platform are routed through one set (arm) of slip rings. Similar sets of power, signal and coaxial lines are available at the aft-mounted platform.

Several control mode combinations are available for operating the DES. Each of the three gimbals may be controlled in a position, velocity, automatic, closed loop or external mode. Manual controls may be used to command the arm, fork, or gondola to any desired position or velocity. In the automatic mode, pre-determined computer-generated G/time profiles are used to drive the centrifuge. Closed loop control by the subject using control sticks, rudder pedals, or other devices is also used. The most common mode of operation of the DES is to provide a velocity signal for the arm, with the gondola resultant vector determined by the arm velocity and the fork vector determined by the arm acceleration. External control of the centrifuge by a simulation computer is frequently used to allow the synchronization of the performance tasks, stress environment, and data acquisition. All external control signals for the centrifuge are processed by the control computer to insure that they do not violate the limits set for the particular experiment being conducted. Overall control of the centrifuge is performed by a dedicated PDP 11/40 mini-computer. The control computer also provides safety monitoring of all drive systems, critical system pressures and temperatures, power supplies, access doors, and other system parameters. If a drive system or other system parameter is out of tolerance, the control computer will initiate a controlled shut-down of the centrifuge. In the event of a major failure, such as primary power outage, a fail-safe mechanical system will apply brakes to all systems and the centrifuge is brought to a stop. Hydraulic accumulators provide a backup hydraulic fluid supply to the hydrostatic bearing to prevent damage to that system.

Several consoles are available for control, monitoring, and experiment support. The machine operator's console is used to control and monitor the operation of the drive systems. The test director's console contains CCTV monitors and instrumentation for monitoring the operation of the centrifuge, observing the subject, and overall coordination of the experiment. The test director's console also contains remote control functions for the simulation computer, and selects the source of external control signals for the centrifuge. The medical monitor's console contains CCTV monitors, EKG monitor and recorder, and other physiological instrumentation for medical monitoring of the subject. The investigator's console contains CCTV monitors, video tape recorders, strip chart recorders, and other experiment specific instrumentation. All consoles have audio communications with the subject and the other consoles.

Signal conditioning and recording may be accomplished both in the gondola or in the medical monitor room. Physiological signal amplifiers are installed in the gondola. Strip-chart recorders, analog tape recorders, video tape recorders, audio tape recorders, and other instrumentation are available in the medical monitor room. Signals may be digitized and recorded on magnetic tape by the simulation computer system. Printouts of the data and the magnetic tape with the recorded data are available for further analysis.

A Gould/SEL 32/77 digital computer and an EAI 680 analog computer are used to generate profiles and for data collection. A PDP 11/34-A mini-computer and an E & S Multi-Picture System are used to generate video display simulations and tracking tasks for the subjects.

USAF HOLLOMAN AFB TRAINING CENTRIFUGE

HISTORY

The newest centrifuge facility in NATO has recently been brought into service by the Tactical Air Command at Holloman AFB, New Mexico, USA. The centrifuge is located at the Physiological Training Center, and is operated by the 833rd Medical Group Physiological Training Unit. This centrifuge was built and installed by Environmental Tectonics Corporation (ETC) of Southampton, PA and is the first in NATO to be procured and configured strictly for the purpose of training aircrew. The first class was trained at this centrifuge on 27 Sep 1988.

SYSTEM PERFORMANCE

This system is capable of a maximum level of 15 G_Z and provides an average onset rate of 6 G_Z per second from a baseline of 1.2 to 9 G_Z. The system is designed to provide full performance with [illegible]ximum payload of 320 kg in the gondola.

SYSTEM DESCRIPTION

The length of the centrifuge arm is 6.1 m, from the center of revolution to the axis of rotation of the gondola. The arm is of monocoque girder design and is constructed of high strength stainless steel. The cross section of the arm is a rectangle (1.066 m wide by 0.457 m high) to the point at which it forks for gondola mounting. The arm weighs approximately 1350 kg. All wiring and plumbing are contained inside the arm.

The gondola is also of monocoque design and a polygon shape. Its dimensions are approximately 3 m long by 2 m wide by 2.5 m high and it weighs approximately 400 kg. The gondola is passively coupled to the G_Z vector. It is mounted in trunion bearings at either end and pivots about its longitudinal axis. Damping of this rotation, to limit overshoot and excessive oscillation, is provided by a hydraulic rotary actuator. The rotary actuator is connected to a closed loop hydraulic circuit with a valve to allow adjustment of the damping force. The interior of the gondola is fitted with a simulated ejection seat which has an electrically driven height adjustment. The seat is adjustable to provide either a 30 deg. or 13 deg. back angle. Rudder pedals are provided for both seat positions and can be adjusted by the rider. The light bar is mounted in a fixed position with a central red light and two sets of green lights. The inner set of green lights is used with the seat in the 13 deg. position and the outer set with the seat in the 30 deg. position. An Alar High Flow Anti-G valve is mounted on a pedestal next to the seat and is at approximately the heart level. The subject is monitored during runs by a CCTV camera mounted in the gondola. A light emitting diode (LED) display is mounted to the left rear of the subject. The number on this display can be changed from the control room. This display is used for training with the rider's head turned in a "check 6" position. This centrifuge can be controlled from inside the gondola (Closed Loop Control) by use of a center control stick, used with the 13 deg. seat position or a side arm controller, used with the seat in a 30 deg. position. A large monitor is mounted in front of the subject and presents a graphically displayed horizon line proportional to the G_z level and a target aircraft tracking task for use with closed loop control. Both heating and air conditioning are provided in the gondola.

Counterweights of approximately 3000 kg and an equipment box are located at the opposite end of the arm from the gondola. The equipment box contains power supplies, amplifiers, a small air compressor for Anti-G suit pressure supply, and the compressor and fan unit for the gondola air conditioning.

The pedestal supports the rotating system. The centrifuge spindle shaft is supported by an upper self-aligning roller bearing and a lower spherical roller thrust bearing mounted in the pedestal.

The emergency mechanical brake consists of a 0.9 m diameter rotor and caliper system which is hydraulically actuated in the event of loss of building power or is selectable from the control consoles in the event of an emergency.

The drive train of the centrifuge consists of a 300 kW, forced air cooled, DC electric motor and a 90 deg. bevel-helical gearbox. Coupling of the drive train is accomplished through special flexible couplings and compression rings. The torque on the compression rings is adjusted such that there is no slippage during normal operations, but in the event of a lock-up of the motor or gearbox these rings would slip and limit the offset rate of the centrifuge to an acceptable level.

Electrical signals to and from the centrifuge are conducted through a series of 70 slip rings. The electrical resistance from the Control Room to the gondola is less than 4 Ohms and the signal to noise ratio is less than 1 microvolt per volt. Sixty shielded wire and 10 coaxial connections are provided.

Control of the centrifuge is accomplished by computer. Speed of the system is sensed by a tachometer on the motor which sends a signal to the computer. System status, G_z profile selection and display, interlock status, system parameters, and real time run data are presented on a series of menus and display overlays. This system is based on an IBM PC compatible machine.

The Control Room consists of 5 consoles for system operation and training.

The Operator consoles (2) house a monitor for system display, a keyboard for computer interface, a digital readout of G_z, Normal and Emergency stop buttons, a Run button, and an indicator which flashes continuously if the system has been configured to exceed 9 G_z. These consoles also contain intercom equipment for gondola / Control Room communications.

Three consoles are available for training instructor use. The first contains a monitor for CCTV display of the trainee, a switch which activates / deactivates the trainee's Anti-G suit, and redundant (to the operator's console) Stop and Run buttons and Exceed 9 G_z display. Controls for CCTV camera pan, tilt, and zoom are also at this console. The second console houses a monitor which displays the same computer information as the operator's monitor. This console also houses the equipment for Video Cassette Recording (VCR) of the subject. The third console houses a monitor display of the subject, Normal and Emergency stop buttons, a G_z digital display and a flexible boom microphone. This console also contains a four-channel strip chart recorder which displays G_z level, and Anti-G suit pressure. Electrocardiogram and cardiotach data can also be displayed if required by the run protocol. A monitor is mounted atop the instructor's console which displays the tracking task image as seen by the subject.

USAFSAM CENTRIFUGE

HISTORY

The centrifuge at the USAF School of Aerospace Medicine (USAFSAM), Brooks AFB, Texas, USA, was brought into service in 1962. In 1984 this facility was upgraded to a computer controlled, all electric drive system by KRUG International of San Antonio, TX. The Control Room and instrumentation systems were replaced at the same time. It is operated by the Crew Technology Division and is used for both aircrew training and research operations.

SYSTEM PERFORMANCE

This centrifuge system is capable of a maximum continuous level of 30 G_z and can provide an average onset rate of 6 G_z per second from a baseline of 1.4 to 13 G_z. This system will provide full performance with a maximum payload of 320 kg in the gondola.

SYSTEM DESCRIPTION

The length of the arm is 6.1 m from the center of revolution to the centerline (axis of rotation) of the gondola. There is a test fixture mounted at the opposite end of the arm from the gondola which is used for equipment test and animal research. The center of this fixture is approximately 3.9 m from the center of revolution of the centrifuge. The arm, gondola and equipment fixture are constructed primarily of steel and the total weight of the rotating assembly is approximately 14,500 kg. The gondola is cylindrical in shape and is 1.83 m in diameter by 1.83 m long and weighs approximately 1750 kg. Non-rotating conical-shaped fairings are installed at each end of the gondola for aerodynamic and appearance purposes. The gondola is passively coupled to the G_Z vector and pivots on trunnion bearings mounted on the centerline at each end. Damping of the gondola rotation is provided by a hydraulic rotary actuator. The interior of the gondola is fitted with a typical ejection seat (ACES II) which can be set at any desired back angle from 0 to 30 degrees. A light bar with a central red light and outer green lights is mounted at test subject eye level and can be adjusted to maintain a standard distance from the subject. A panel is provided for mounting any type of Anti-G valve at approximately the heart level. The subject is monitored during runs by a CCTV camera mounted in the gondola. A light-emitting diode (LED) display is mounted to the left rear of the subject. The number on this display can be changed from the control room. This display is used for training with the rider's head turned in a "check 6" position. This centrifuge can be controlled from inside the gondola (Closed Loop Control) by use of a center control stick, used with the 13 deg. seat position or a side arm controller, used with the seat in a 30 deg. position. A large monitor is mounted in front of the subject and presents a graphically displayed horizon line proportional to the G_Z level and a target aircraft tracking task for use with closed loop control. Both heating and air conditioning are provided in the gondola. The gondola also houses equipment racks for mounting instrumentation and experiment support equipment. Connection and amplification facilities are provided for 20 twisted pair of wires which connect through the slip rings to the control room. The gondola has 115V 60 Hz, 115V 400 Hz, and DC power.

The emergency mechanical brake consists of a large band brake system which is pneumatically actuated in the event of loss of building power or is selectable from the control consoles in the event of an emergency.

The drive train of the centrifuge consists of four 190 kW, forced air cooled, DC electric motors which are rated for 200% operation for short time periods. This permits the application of up to 1500 kW to the rotational system. These motors are located in a sub pit below the main centrifuge room. This pit also houses the slip ring assembly and the lubrication system. The centrifuge spindle shaft is supported by upper and lower roller bearings mounted in conical-shaped pedestal. Power is transmitted to the arm from the drive motors by four pinion gears which interface with a large ring gear attached to the arm. Full flow lubrication is maintained at each gear interface during centrifuge operation. All gear drive and lubrication nozzles are located in the pedestal.

Electrical signals to and from the centrifuge are conducted through a series of 200 slip rings. The electrical resistance from the Control Room to the gondola is less than 4 Ohms and the signal to noise ratio is less than 1 microvolt per volt. Six coaxial connections are also provided for CCTV and low level signals.

Control of the centrifuge is accomplished either manually or by computer. System status, G_Z profile selection and display, interlock status, system parameters, and real time run data are presented on console displays in the control room.

The Control Room consists of 8 consoles for system operation, research, and medical monitoring. The Operator consoles (3) house a monitor for system display, a keyboard for computer interface, a digital readout of G_Z and arm RPM, an X - Y plotter which plots G_Z v.s. Time, a series of interlock system status LEDs and the required system control and monitoring displays. The Central Observer console contains a monitor for CCTV display of the trainee, and a switch which, when released, activates the centrifuge brake. Controls for CCTV camera pan, tilt, and zoom are also at this console. The Scientist has three consoles for his use. The first contains various time displays and remote control of data recording equipment. The second console houses an eight-channel paper recorder for acquiring and displaying research data. The third console houses a monitor and keyboard terminal for interface with the PDP 11/34 data computer. The Medical Monitor console contains an 8-channel paper recorder for display of medical and run data such as G_Z level, G Suit pressure, electrocardiogram and cardiotach data. A CCTV monitor is also mounted in this console. A monitor which displays the tracking task image as seen by the subject is also mounted in the control room.

Signal conditioning and recording are done in the Data Room. Data recording is available in both analog and digital format with analog to digital conversion and some real-time analysis being accomplished on a PDP 11/34 laboratory computer. Analog signals are recorded on two 8-channel paper chart recorders and two 16- channel magnetic tape recorders. A VCR for recording the centrifuge subject is also located in this room.

U.S. NAVY DYNAMIC FLIGHT SIMULATOR

HISTORY

The U.S. Navy centrifuge facility at the Naval Air Development Center, Warminster, PA, USA, is actually made up of two systems: the Human Centrifuge and the Dynamic Flight Simulator (DFS). The Human Centrifuge was brought into service in 1952 and was upgraded in 1964 with major modifications to its structure and control systems. This system is now used for aircrew training, research, procedures development, and equipment testing. This facility is industrially funded and may be used for a fee by private industry and government agencies.

SYSTEM PERFORMANCE

This centrifuge system is capable of a maximum continuous level of 40 G_Z and can provide an average onset rate of 10 G_Z per second from a baseline of 1.5 to 15 G_Z. This system will provide full performance with a maximum payload of over 18,000 G-kg.

SYSTEM DESCRIPTION

The length of the arm is 15.24 m from the center of revolution to the centerline (axes of rotation) of the gondola. The arm is a tubular steel truss structure. The Human Centrifuge / DFS is a massive structure with a total rotational mass of 135,000 kg. The gondola, which houses the DFS, is spherical in shape and is about 3 m in diameter. The gondola is attached to the arm by means of a two gimbal system, an outer roll gimbal and an inner pitch gimbal. Each gimbal is driven by an electro-hydraulic system located on the arm near its hub. The gondola has upper and lower hemispherical caps which are removable for insertion of gondola interiors. The gondola houses the DFS, a reconfigurable, multi-purpose aircraft cockpit with active instruments, flight controls, and computer-generated programmable, full color displays including a head-up display. Environmental controls including altitude (up to 30,500 m), heating, and air conditioning are also provided in the gondola.

The main drive for the centrifuge consists of a single 12,000 kW direct drive DC electric motor.

Electrical power and instrumentation signals to and from the centrifuge are conducted through a set of 124 slip rings. These are made up of 15 single shielded data lines, 74 shielded pair instrument and control lines, 16 electrical power lines capable of carrying up to 15 amps, and 19 coaxial lines for CCTV and Cathode Ray Tube (CRT) display use. Data multiplexing on any of the signal quality slip rings is also available.

Control of the centrifuge system is accomplished using three Electronic Associates Inc. model PACE 231R analog computers. Gondola attitude is controlled by a complex algorithm which not only resolves the acceleration vectors for a correct G_z solution during onset and offset but also compensates for the subject's perceived angular motions and rates for a more realistic flight simulation. System status, G_z profile selection and display, interlock status, system parameters, and real time run data are presented on console displays in the control room.

Complete data monitoring and recording facilities are provided at the Experiment Control Station and the Control Room.

HUMAN CENTRIFUGE FACILITY
KONIGSBRUCK, Nr DRESDEN
GERMANY

This facility, formerly in East Germany, has, since unification, become available to NATO researchers. Designed and manufactured by Austria Metall, AG, its installation was completed in 1986, making it one of the more modern centrifuges currently available. The centrifuge arm is an open lattice of welded steel tubes which carries an adjustable massive counterbalance and a bolt-on yoke assembly. The arm is directly driven by a 900 kw (r.m.s.) electric motor capable of a peak 2.5 MW output with a power consumption of 2.5 kVA. An onset rate of 5G/s can be achieved from a 1.4G baseline, with proportionately lower onset rates from baselines down to 1G.

The gondola is of riveted sheet metal construction with windows which can be screened as required. It has a payload of 500 kg and is carried on the yoke in a double gimble which provides active control in both pitch and roll. Hydraulic activators permit rates of up to 1.0 rad/s in pitch and 1.2 rad/s in roll, the power source being mounted at the centre of the arm with electric power being provided through slip rings beneath the main motor. Catwalks on top of the centre part of the arm allow access to the signal slip rings.

At the end of a run the gondola is parked automatically alongside a hydraulically lowered platform which overhangs the pitch control gimble. This provides access to a gullwing door which opens upwards to clear the upper third of the outer wall, and outer two thirds of the roof of the gondola. Underbody panels can also be removed to provide additional access to gondola mounted equipment, and to the subject in the event of an emergency.

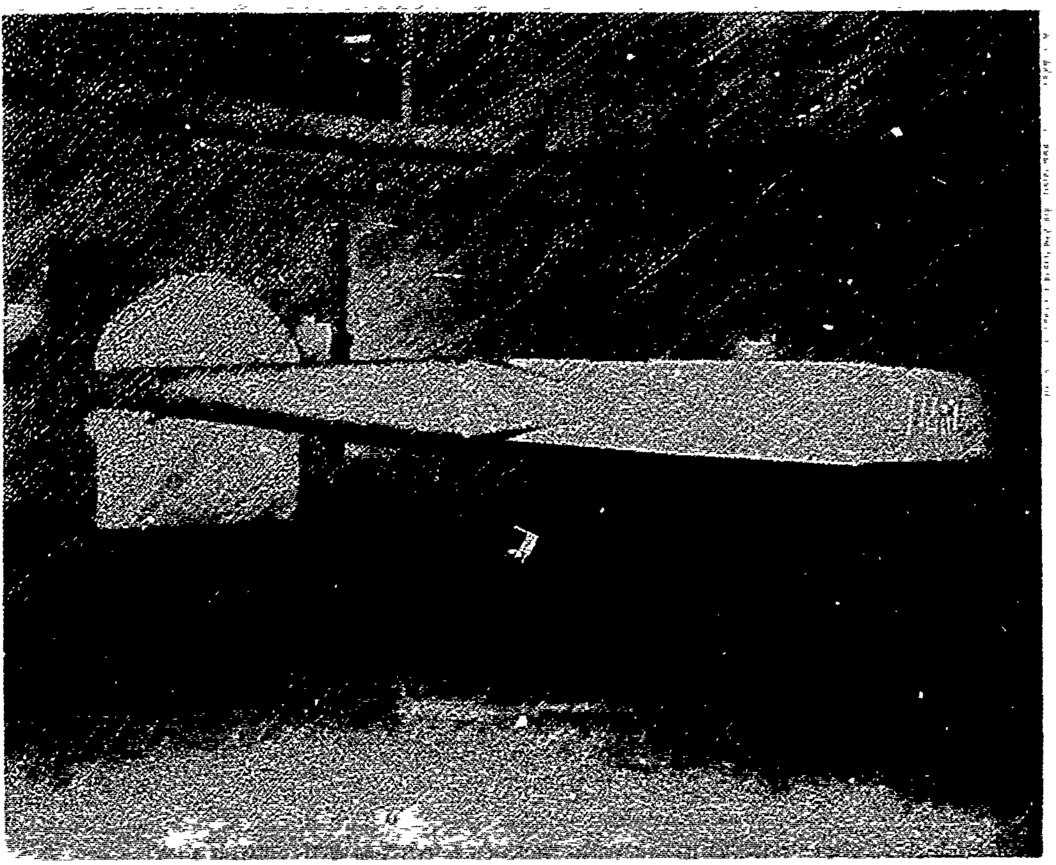
The centrifuge is computer controlled with software programming of run profiles, and is currently being used to examine the effect on human tolerance of $+G_z$ following $-G_z$ exposures.

SUMMARY

Since aircrew must not only survive but also operate efficiently in the high G environment encountered in modern fighter aircraft, centrifuge "G training" has become highly desirable. Many countries are, either upgrading old centrifuge facilities or procuring new ones to meet this training need. A number of attributes are required of a centrifuge to provide an adequate training environment. A training centrifuge should be capable of attaining at least 9 G_z with an average onset rate of 3.5 G_z per second. System safety should be of primary concern in the design of a training centrifuge and all rotational or load bearing structure should be designed with a safety factor of at least 1.5. The alignment of the gondola with the G_z vector must be maintained but active computer control or pitch gimballing is probably not required of a training centrifuge. The arm length of most centrifuges is at least 6 m but excellent training has been accomplished on a machine with an arm length of 4 m. Computer control of the centrifuge with optional pilot control is considered mandatory for good aircrew training. There are 11 centrifuges in NATO used for training. These are located in Canada, France, Germany, The Netherlands, Turkey, United Kingdom, and 5 in the United States.

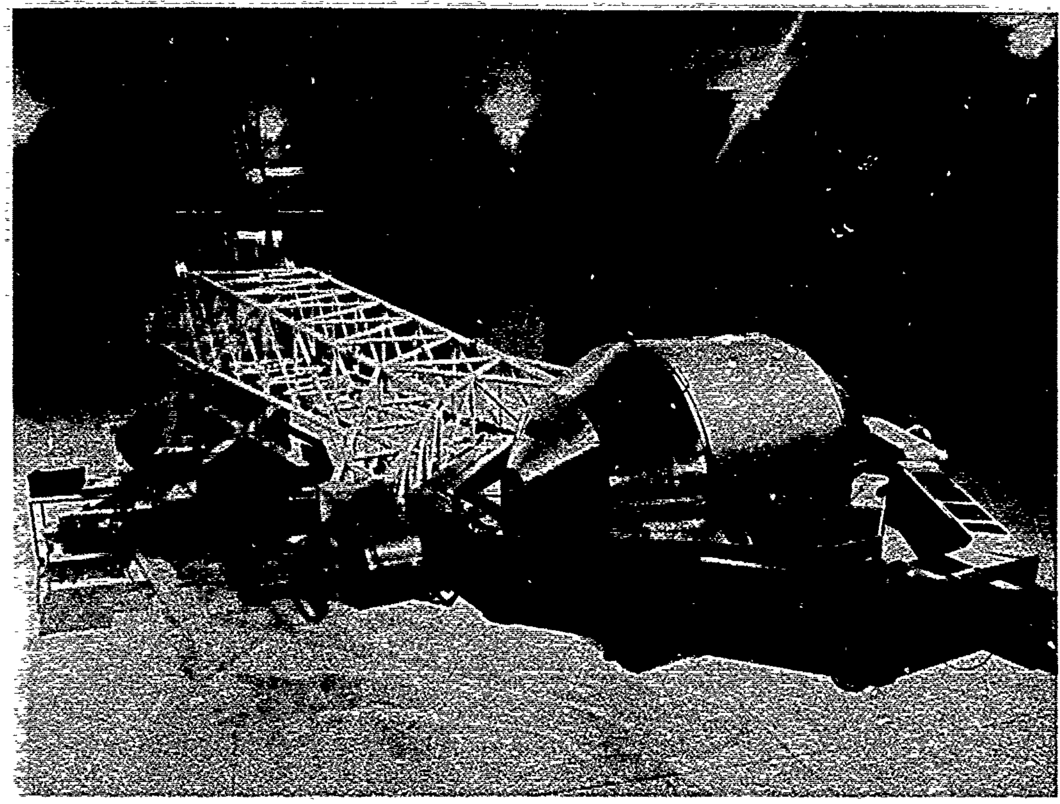
CENTRIFUGEUSES DES PAYS DE L'OTAN.

L'importance des facteurs de charge a rendu nécessaire l'entraînement en centrifugeuse des équipages d'avions de combat modernes pour permettre leur survie mais aussi pour améliorer leur efficacité opérationnelle. De nombreux pays modernisent leurs centrifugeuses ou en acquièrent de nouvelles pour satisfaire ce besoin. Pour garantir un entraînement correct, les centrifugeuses doivent être dotées d'un certain nombre de caractéristiques minimales: mise en accélération de 3.5 G/s et niveau de 9 G. La sécurité du système doit être une des principales préoccupations des concepteurs de centrifugeuses d'entraînement. Un coefficient de sécurité d'au moins 1,5 devrait être pris pour l'étude du dimensionnement des structures porteuses ou en rotation. L'alignement de la nacelle avec le vecteur accélération doit être maintenu mais l'asservissement de l'inclinaison de la nacelle en fonction de la vitesse de rotation du bras n'est pas nécessaire pour les centrifugeuses d'entraînement. La longueur du bras de la plupart des centrifugeuses est d'au moins six mètres mais d'excellents entraînements ont été effectués sur des centrifugeuses de quatre mètres. Le contrôle de la centrifugeuse par un ordinateur avec la possibilité pour les pilotes de commander directement leurs accélérations est considéré comme une nécessité pour un bon entraînement. Il y a onze centrifugeuses dans les pays de l'OTAN. Le Canada, la France, la Grande-Bretagne, les Pays-Bas, la République Fédérale d'Allemagne et la Turquie en ont chacun une. Les Etats Unis d'Amérique en possèdent cinq.

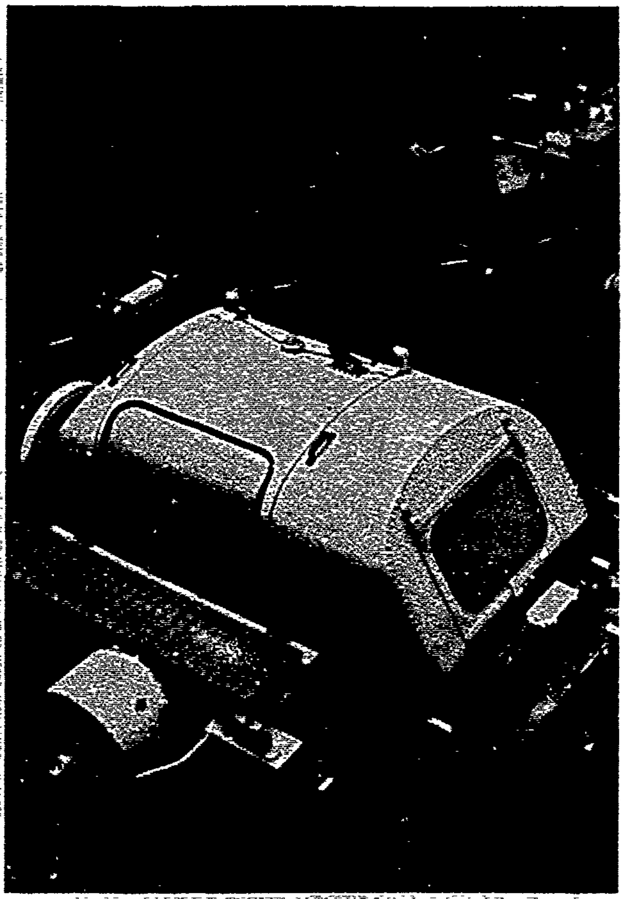


CANADIAN CENTRIFUGE
Defence and Civil Institute of Environmental Medicine (DCIEM), Toronto, Ontario, Canada

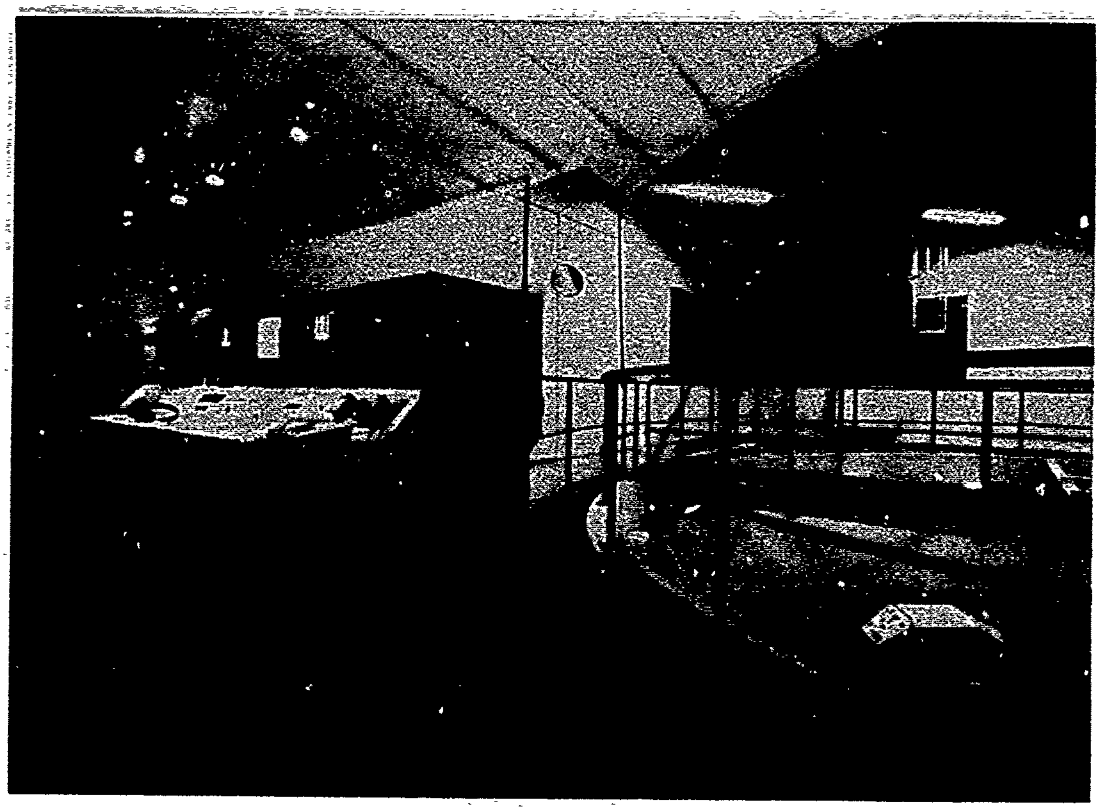
FRENCH CENTRIFUGE
Laboratoire de Médecine Aérospatiale, Brétigny, France



GERMAN CENTRIFUGE SHOWING GONDOLA SYSTEM WITH GIMBAL RING
Air Force Institute of Aerospace Medicine, Fürstenfeldbruck, Germany

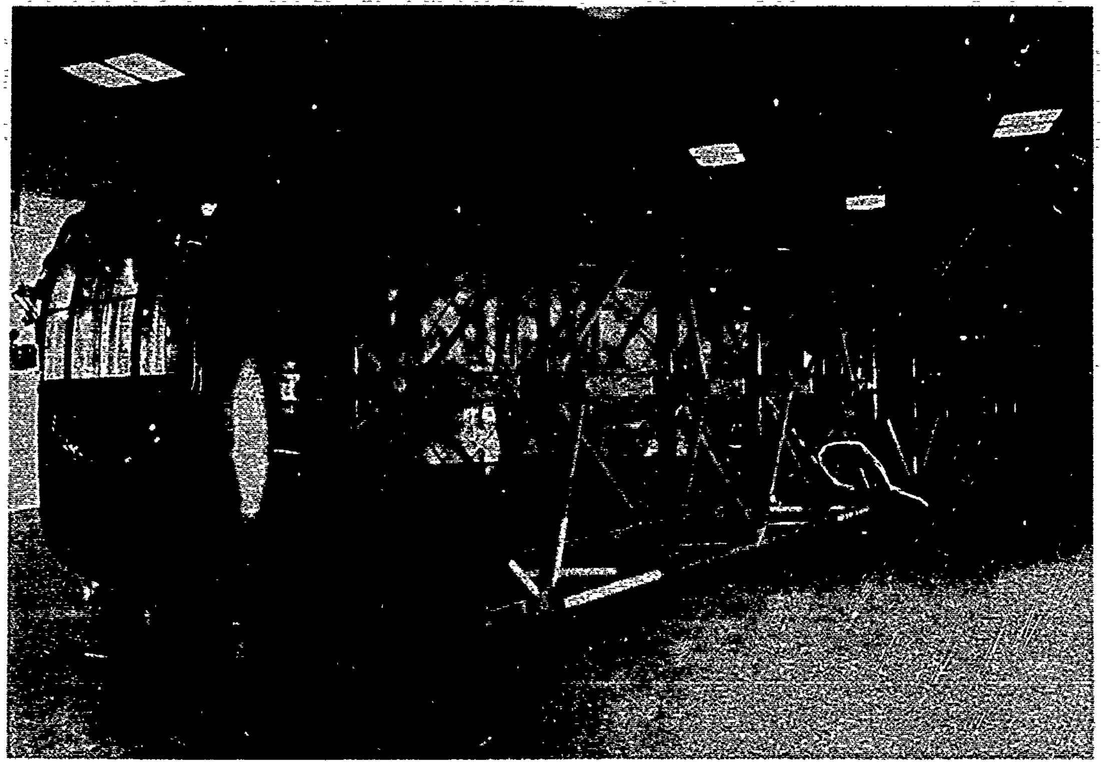


GERMAN CENTRIFUGE SHOWING THE GONDOLA, PITCH AND ROLL GIMBAL RINGS
Konigsbruck, Germany

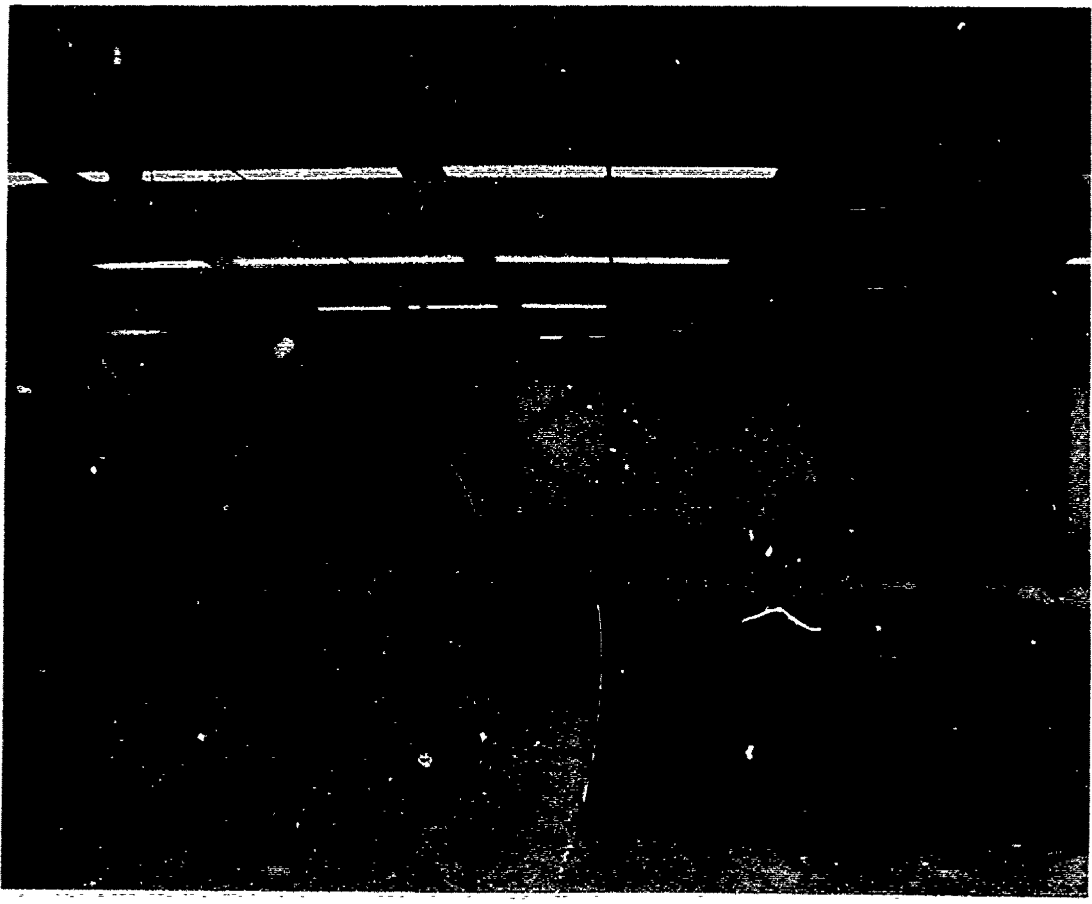


DUTCH CENTRIFUGE
National Aerospace Medical Centre, Soesterberg, The Netherlands

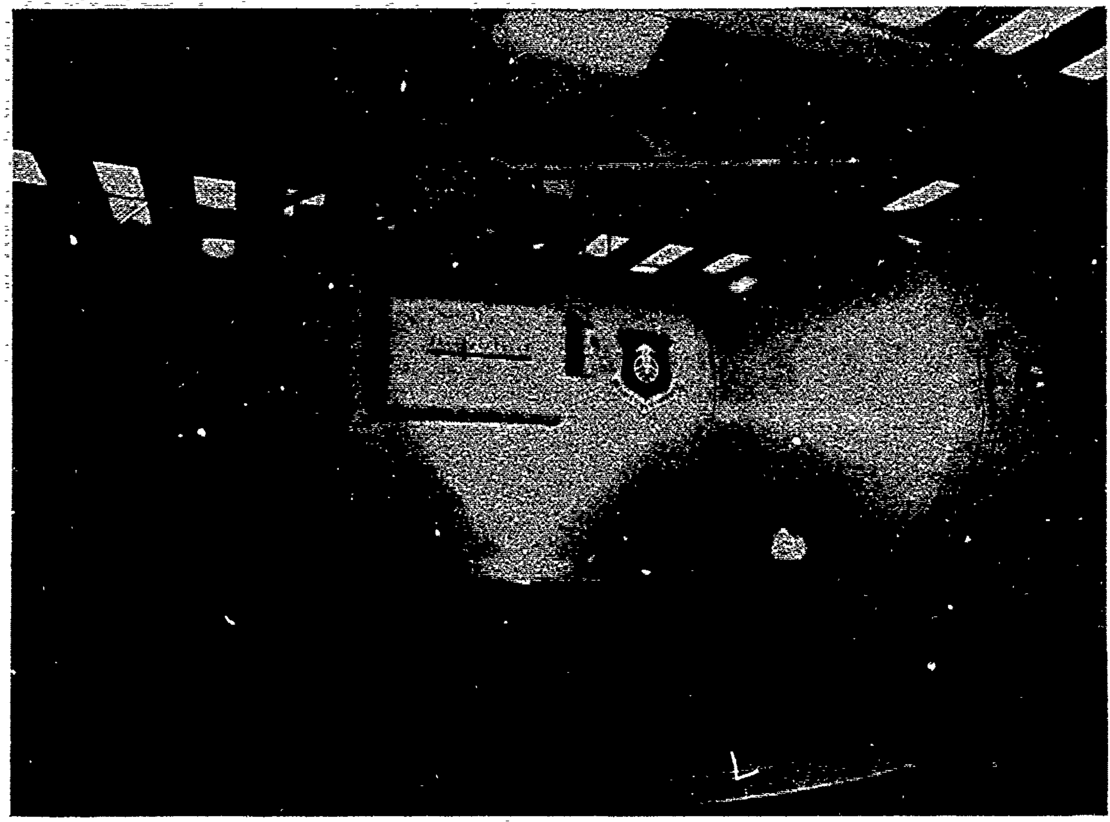
TURKISH CENTRIFUGE
Gülhane Academy of Medicine, Aerospace Medical Centre, Eskişehir, Turkey



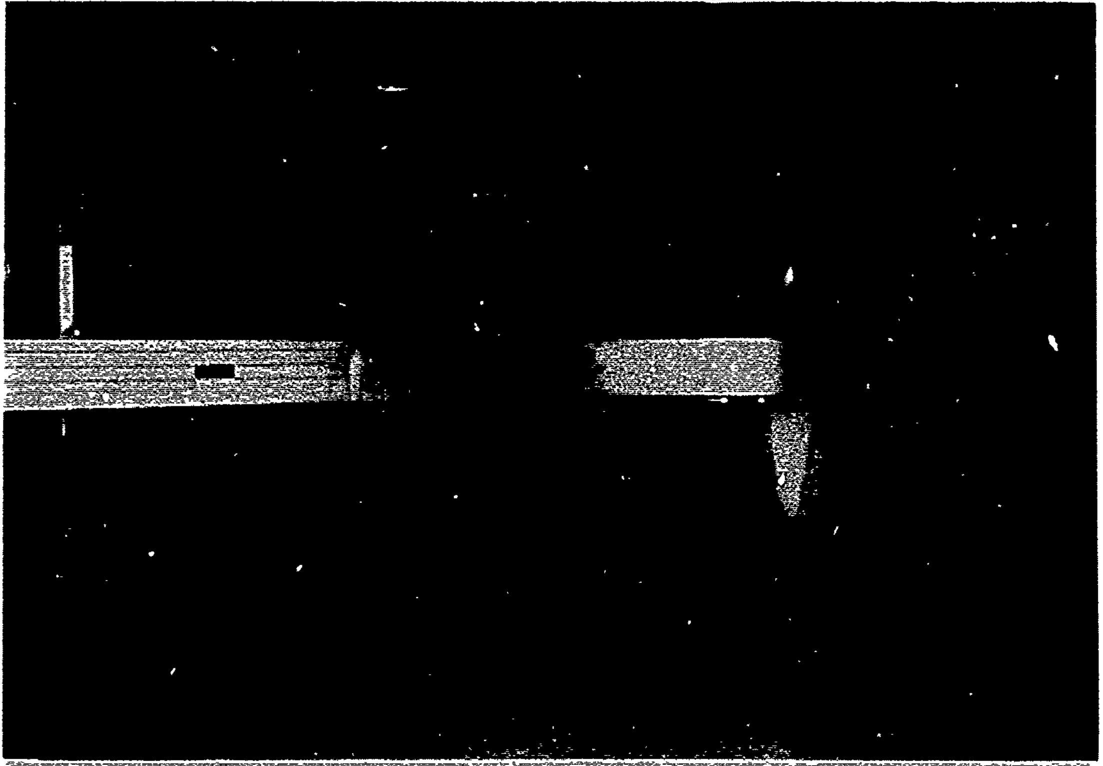
BRITISH CENTRIFUGE
Royal Air Force Institute of Aviation Medicine, Farnborough, Hampshire, United Kingdom



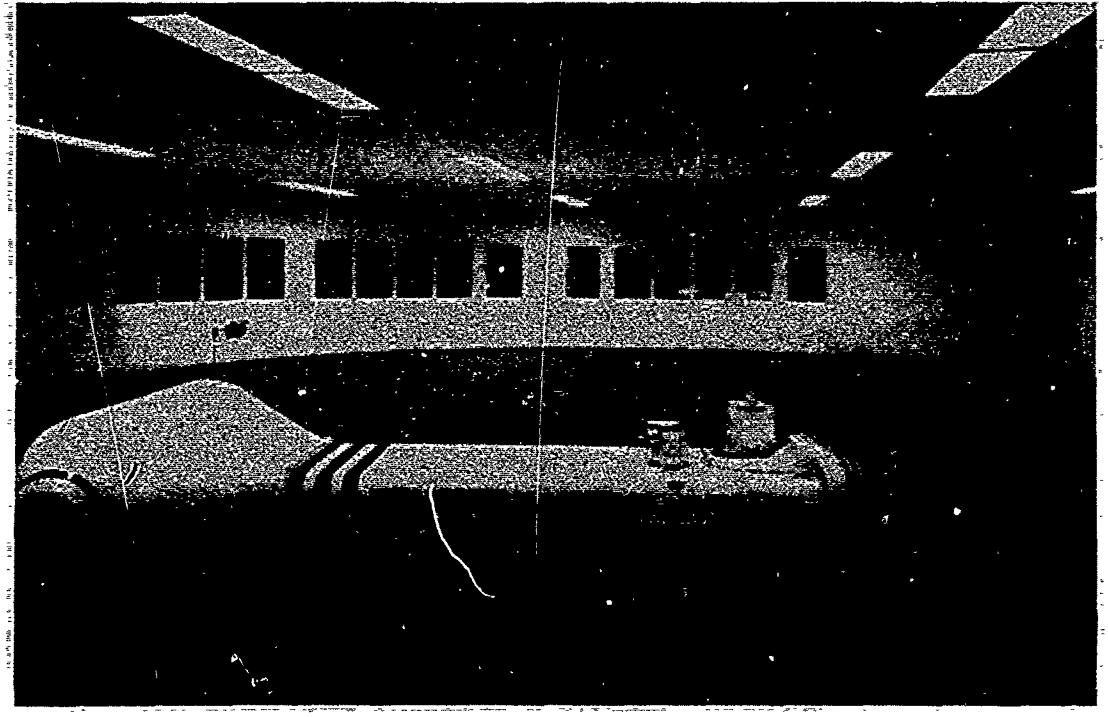
USA NASA CENTRIFUGE
Ames Research Center, Moffett Field, California, United States



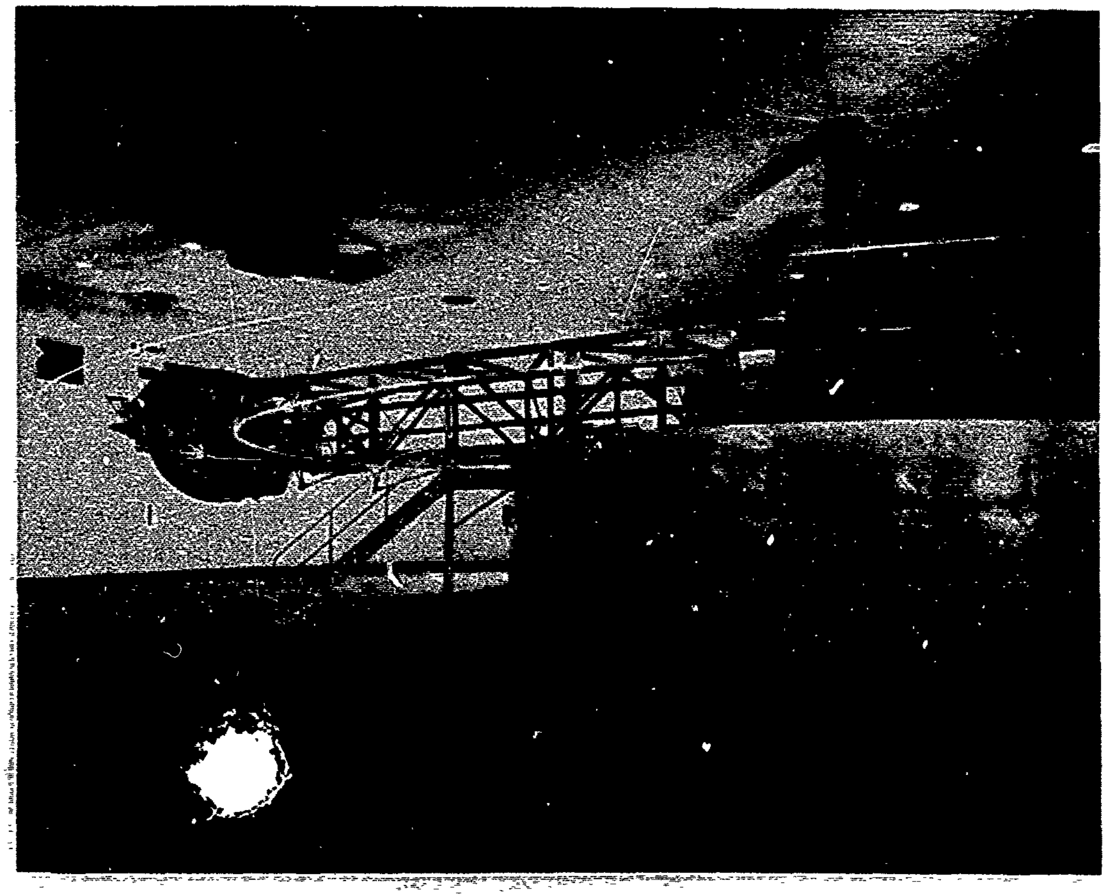
USAF DYNAMIC ENVIRONMENT SIMULATOR
Armstrong Aerospace Medical Research Laboratory, Wright Patterson AFB, Ohio, United States



USAF TRAINING CENTRIFUGE
Tactical Air Command, Holloman AFB, New Mexico, United States



USAFSAM CENTRIFUGE
USAF School of Aerospace Medicine, Brooks AFB, Texas, United States



US NAVY CENTRIFUGE
Naval Air Development Center, Warminster, Pennsylvania, United States

CHAPTER 7
PHYSICAL CONDITIONING - PHYSIOLOGIC CONSIDERATIONS

INTRODUCTION

The pilot's ability to tolerate high acceleration forces relies mainly on the anti-G straining maneuver (AGSM) that will result in a 4 G addition of G-tolerance over relaxed G tolerances if performed in a proper way by a pilot in good physical condition. The AGSM is a voluntary isometric contraction of much of the body's major musculature that, in conjunction with a forced prolonged exhalation against a closed or partially closed glottis, results in an increase of pressure within the chest. This increased chest pressure is transferred to the heart resulting in an equal increase in arterial blood pressure at the heart (see Chapters 2 and 3).

Although the AGSM has always been known to be very demanding physically, the necessity to be in excellent physical condition, particularly regarding strength and anaerobic capacity, was not realized until the last decade. Earlier research by Cooper and Leverett (65) and Klein et al (120) failed to detect any change in relaxed G-tolerance with an improvement in aerobic capacities. These results are not unexpected, however, since relaxed G- tolerance is a function of arterial pressure without the influence of the AGSM, and all types of physical exercises have very little residual effect on this blood pressure.

On the other hand, support for the pilot is most needed above relaxed G levels while the AGSM is being performed. It is the physical activity of the AGSM that benefits most from a physical conditioning program. This hypothesis was first proposed in a study conducted at the USAF School of Aerospace Medicine (USAFSAM) in 1978 when the effect of weight lifting that increased whole body muscular strength was compared with no exercise controls and distance running on a G-tolerance measurement that required the subjects to use an AGSM (76,75). This G-tolerance was called the Simulated Aerial Combat Maneuver (SACM) that exposed the subject wearing a functioning anti-G suit to a controlled G response of 4.5 G for 15 sec and then 7 G for 15 sec, repeating this profile until fatigue caused the subject to stop the centrifuge run (49) (Fig. 3-6). This type of G-tolerance measurement allowed subjects for the first time to be tested for physical endurance using different G levels similar to the G environment found in High Performance Aircraft. This study found that a weight-lifting program for 12 weeks that significantly increased their strength, increased their G-duration tolerance by 53%. On the other hand, the distance runners that had significantly increased their aerobic capabilities did not change their SACM tolerance from the control subjects who did no exercises (Fig. 7-1). These results were later confirmed with a 34% increase in SACM tolerance by a similar weight-training study conducted at the Karolinska Institute, Stockholm, Sweden (186).

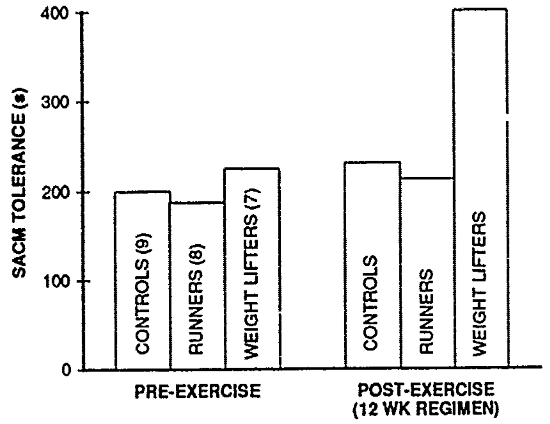


Fig. 7-1
The effects of weight lifting and distance running on SACM tolerance times (76). The number of subjects per group is in parentheses.

ENERGETICS OF THE AGSM

The Swedish study by Tesch et al (186) determined that the principal energy source for these endurance G experiments was anaerobic. They measured blood lactate and observed that it increased in direct proportions to the length of the SACM (Fig. 3-8). They also found that their weight- lifting program had increased the anaerobic power of their subjects that was related to an increase in the slow contractile speed component of the muscle strength. A later study at USAFSAM examined the anaerobic aspects of the AGSM in considerable detail, defining an alactate component of the anaerobics during the first 10 sec of a high G exposure (53). This study therefore confirmed the results of Tesch (185) about the anaerobic nature of the AGSM.

Establishing that the energy basis for the AGSM is anaerobic allows for the application to high G of the large body of physiologic knowledge about anaerobics, physical conditioning, and muscle energetics and metabolism that has been learned at 1 G (Fig. 7-2) (40,153). The early energy source (first 10 sec) of the AGSM when energy is produced with neither the production of lactate nor the use of oxygen is adenosine triphosphate (ATP) splitting (53). This phosphagen energy reserve is immediately reenergized at the beginning of the rest period. Additional sources of energy that are used as the AGSM continues beyond 10 sec and are fueled principally by anaerobics are muscle creatine, creatine phosphate (CP), ATP, and glycogen. All of these energy sources are increased following heavy resistance training (143). As these energy sources are increased, the length of time that a maximal voluntary contraction (MVC) can be sustained is increased, as well as the number of repeated contractions. The MVC of certain muscles must be considered directly correlated to the ability of an individual to perform the AGSM.

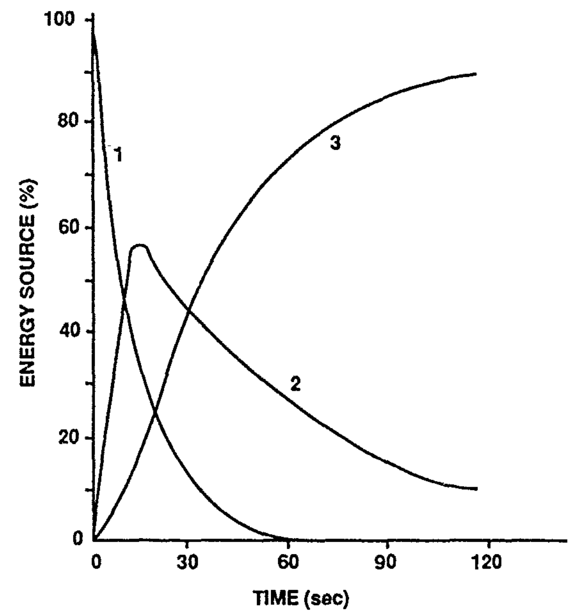


Fig. 7-2
The sources of energy used by skeletal muscles as related to duration of exercise (1 = phosphagen; 2 = anaerobic; 3 = aerobic; from 153).

It is generally conceded that as an individual tires, the MVC of most voluntary muscles is reduced at a rate of about 1% per second (40). If this rate of reduction in MVC is applied directly to the AGSM, and assuming that 100% of the MVC is required to tolerate 9 G (an improvement of 4 G above resting G tolerances with the help of an inflated anti-G suit, see Chapter 3), then after 25-30 sec, 25% of 4 G or about 1 G of a pilot's high-G tolerance is lost. This tolerance loss is immediate and is not obvious to the pilot. Consequently, after several seconds of high G SACM if a pilot attempts again to perform a maximum 9 G maneuver, G-LOC may likely result. It is important, therefore, for pilots to routinely conduct heavy resistance training in order to maintain a high level of energy reserve in their muscles that will significantly slow this process of fatigue and allow them to pull high G later in the SACM.

More recently, the importance of muscular strength and anaerobic power in performing the AGSM during a SACM test profile was determined using the Wingate test. This test measures lower body muscle anaerobic power for a duration of 30 sec at 5 sec intervals. The results of this test were directly correlated (r = 0.77) with their 4.5-7 G SACM to fatigue in 10 subjects (196) (Fig. 7-3). In the same study, the importance of muscular strength in G-duration tolerance was also shown with a significant correlation of (r = 0.79) between thigh and calf circumferences and SACM tolerance and (r = 0.85) with arm and chest circumference. The "correlation of determination" from which the percentage of SACM is determined by the represented parameter is calculated by "r^2"; e.g., r = 0.77 or r^2 = 0.59, or 59% of the SACM is a function of the physiologic factors determining the Wingate test. The thigh and calf circumferences account for 72% of the SACM. Clearly these correlations demonstrate the importance of muscular strength in ACM tolerance for pilots. The use of the Wingate test as a method of selecting pilots for high-G tolerance is discussed in Chapter 9.

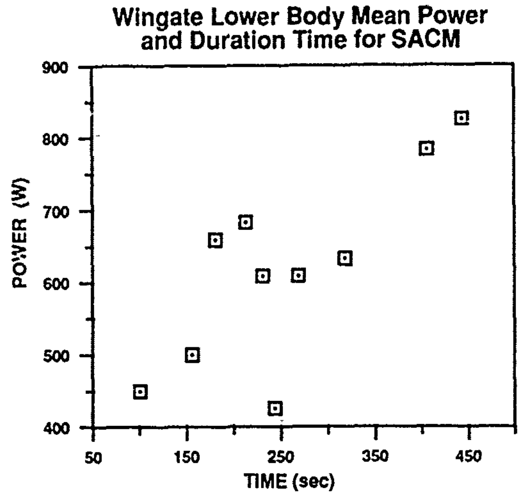


Fig. 7-3
The anaerobic power (w) of individuals measured as their lower body mean power, is correlated to their SACM tolerance (196).

Since the Epperson et al (76) study had found the abdominal muscles to be most affected by the muscle-strength conditioning program and directly correlated to individual increases in SACM tolerance, a study was conducted to determine if only abdominal muscle strengthening would increase SACM tolerance. This study conducted by Spence et al (178) found that such a limited program was not beneficial for increasing G-duration tolerances. However, they did find that regular (weekly) exposure to the SACM was important in maintaining their G-duration tolerances. Abdominal muscle isometric training only was likewise found inadequate to increase G tolerance in pilots by Balldin et al (12).

Since these many studies have clearly shown that weight lifting that increases "whole body" muscle strength will increase G-duration tolerance, this type of exercise is either required of or recommended to fighter pilots in many countries (9,16,112,114,152,185). The current status of the position of NATO countries on physical conditioning programs for aircrew is shown in Table 7-1.

AEROBIC EXERCISE

Aerobic-based exercises have been found to be ineffective in altering duration tolerance to the SACM (Fig. 7-1) (75). In addition, individuals who are highly aerobically fit are considered at greater risk during high G exposures because of increased heart arrhythmias, a greater incidence of G-LOC, and a slower recovery from G-LOC (109,209). Also, aerobically fit individuals are more prone to motion sickness (14,209).

PHYSICAL TRAINING CONCERNS IN DEVELOPING A G-TOLERANCE IMPROVEMENT PROGRAM

Introduction

Since a muscle strength training program specifically for enhancing the AGSM has never been developed, only generic total body weight training programs are available to pilots to improve their G tolerance. Consequently this

Table 7-1.
Current Status of Position of NATO Countries on Physical Conditioning Programs for Aircrew as of OCT 89.

Country	Service/Command	Requirement	Exercise	Amount	Equipment	Provided	Remarks
CANADA	CF-18 pilots	Voluntary	Resistance	4x/week	Hydra-Gym(H-G)	Yes	Pilot acceptance
USA	USAF/HQ TAC	Lift/RTU Mandatory	Resistance	3x/week	H-G	Yes	Began in JUN 86
			Aerobic	3x/week	Hydraulic for Grav.Weights G-W	Yes	Excessive-discouraged
		HPFP Voluntary	Resistance	3x/week	H-G, H or GW	Yes	Not in Sqd. Bldg
			Aerobic	3 mi, 3x/week	N/A		Excessive-discouraged
	AFISC (Recommendations) 27 MAY 86	Voluntary w/mandatory option all FAR aircrews	Resistance		H-G	Yes	Time made available Convenient equipment
	USN/F-18 pilots	Voluntary	Resistance	4x/week	G-W	Yes	
Greece	F-16 Mirage 2000	Voluntary	Resistance	3x/week	Hydraulic weights	Yes	In Sqd. Bldg
Netherlands	TAC	Voluntary	Resistance	3x/week	Hydra Gym	Yes	In Sqd. Bldg
UK	STC/SC/RAFG	Voluntary			Multigym	Yes	No formal policy
Italy	Fighter pilots	Voluntary			Various	Occasionally	No formal policy
Norway	F-16 pilots	Voluntary	Resistance	3x/week		Yes	
Denmark	F-16 pilots	Voluntary	Resistance	3x/weeks	Mini/Gym 500x	Yes	Partly accepted
W. Germany							Waiting for Eurofighter
France	CAFDA-FATCA	Voluntary	Anaerobic	2x/week first 3 months 1x/week afterwards	Weights	Yes	In Sqd. Bldg. controlled by Gym. instructor.
Spain	Fighter-pilots	Voluntary	80% anaerobic 20% aerobic	3x/week	Various	Yes	
Belgium	F-16 pilots	Voluntary	Resistance	3x/week		Yes	Not in Sqd. Bldg
Portugal	Fighter-pilots	Voluntary	Resistance			Yes	In Sqd. Bldg.
Turkey	F-16	Voluntary*	Anaerobic + aerobic	Optional	Mini Gym	Yes	No Sqd. Bldg.

LIFT = Lead In Fighter Training
HPFP = High Performance Fighter Pilot
AFISC = Air Force Inspection Safety Center
RTU = Replacement Training Unit
USAF/HQTAC = US Air Force Headquarters Tactical Air Command
FAR = Fighter Attack, Reconnaissance

* Mandatory first 3 months of training afterwards voluntary.

chapter provides the basics for only a nonspecific type of training program. A detailed generic type of physical conditioning program for aircrew of high performance aircraft was recently published as a joint U.S. Air Force (USAF) and U.S. Navy (USN) report entitled "Physical Fitness Program to Enhance Aircrew G Tolerance." The following physical conditioning concepts are in part based on that report (66).

Only general concepts regarding the application of a generic muscle strength-building program to the pilot are addressed herein. Books on specific exercises and how to safely perform them are available at libraries and book and sporting goods stores —particularly those that specialize in physical conditioning equipment. The USAF/USN report (66) would be helpful to aircrew members interested in increasing strength to improve G tolerance. Since working with weights requires exacting techniques, getting professional advice from someone knowledgeable in the area is strongly urged. Poorly executing correct techniques or using the wrong techniques can cause serious physical damage resulting in medical problems that can be permanent and perhaps jeopardize a pilot's flying future.

Exercise Program Considerations

Physical training for tolerating high G forces is similar in many ways to the training required for short-duration, high-intensity athletic competition such as the 100-m sprint. In this event, relevant muscle groups have to provide large amounts of energy for a short period of time. This rapid requirement is only possible using energy that can be released in the muscles without the presence of oxygen (anaerobic and phosphagen sources). On the other hand, long-duration events obtain energy from oxygen (aerobic metabolism—see Fig. 7-2). Consequently, anaerobic training should be given higher priority than aerobic training in a physical fitness program for pilots.

The design of a specific weight-training program to increase G tolerance must consider the following:

Exercise Specificity:

For optimal improvement in G tolerance, the exercise program must focus on the respiratory and skeletal muscle movements that are used in the AGSM. To simulate the AGSM, a full breath should be taken before the lifting phase during a resistance effort. As the weight is raised, straining against a partially closed glottis should continue during the lift. However, one should not build up full pressure in the chest against a closed glottis, since at 1 G dangerously high arterial blood pressure may result.

Exercise intensity:

For maximal benefit in developing strength, the load for those exercises that use weights (see following section on specific exercises) should be 80-90% of the maximum weight-lifting capability at one time for each exercise. Another measure of the resistance for each exercise is the load which can be achieved for the indicated number of prescribed repetitions. When the aircrew can perform one or more repetitions beyond the specified limit, more weight or resistance should be added. In a muscle strength conditioning program, repetitions for the various exercises will range from 5-10, depending on the exercise.

Exercise duration:

The conditioning program must be performed with 5-10 repetitions per set with 2 or more sets per exercise period. A "set" refers to the number of repetitions completed. In a muscle strength conditioning program, sets for various exercises range from 2-5.

Rest periods:

Specific rest periods should be rigorously adhered to between sets and between exercises, depending on the program specifications. The duration of the rest period is extremely important since it will affect the exercise program loads and the physiological stress of the workouts. Rest periods should be between 2-3 min and at least equal to the amount of time spent in performing the set.

Exercise frequency:

A minimum of 24 hours should elapse between exercise sessions. No more than four training sessions should be completed in a week. For conditioning to improve G-tolerance, both strength and endurance exercises are recommended; e.g., perform exercise program on alternate days such as strength on Monday, endurance on Tuesday, rest on Wednesday, strength on Thursday, and endurance on Friday. Aerobic conditioning can be performed whenever it is convenient. An aerobic conditioning program for pilots is briefly discussed later in this chapter.

Exercise order:

Muscle groups most useful in performing the AGSM should be exercised first. Muscular endurance workouts are characterized by paired exercises. A set of the first exercise is performed and, without rest, a set of the second paired exercise is performed. For example, one might perform 10 repetitions of the bench press immediately followed by 10 repetitions of the shoulder shrug. This resistance training is known as a "super set." A super set is followed by a 30-60 s rest, whereupon a second super set is done. Two to three super sets per pair of exercises can be used. The number of repetitions per exercise set ranges from 10-20, depending on the exercise performed. Paired exercises represent components of the high-intensity, muscular endurance, resistance training program.

Warm-up and cool-down:

Each day, the conditioning program should begin with a gradual warm-up and stretching session of 5-10 min. Also, approximately 5-10 min of whole-body stretching should be performed after exercising to minimize soreness.

Program assessment:

The effectiveness of any training program should be periodically assessed by examining some quantifiable performance parameters; e.g., an increase in maximum weight-lifting capability. Participation in a 12-week conditioning program should result in a 10-20% improvement in strength in all muscle groups exercised.

Exercise timing with flying:

The demands of exercise on the cardiovascular and metabolic systems are such that more than 3 hr should elapse before assuming high-G flight duties. This timing is particularly important as intense exercise can lead to temporary fatigue due to exhaustion of muscle energy reserves, noticeable muscle tremor, and possible post-exercise hypotension—low arterial blood pressure may persist that will reduce relaxed G tolerances.

Isokinetic Exercise:

Using an isokinetic method for training aircrew may represent some advantages compared to the more traditional methods. Isokinetic muscle contraction is a contraction under constant velocity which is very efficient at building up strength and endurance. Isokinetic training also reduces the warm-up period and minimizes muscle soreness.

Specific Exercises

The specific exercises that are considered most useful for pilots to improve their G tolerances are: Arm curl, lat pull, military press, bench press, leg press, and sit-up/leg raise. Neck flexion/extension exercises are recommended but probably are not useful in improving G tolerance.

Neck Exercises and Neck Injury During G

During flight events that require visual scanning during high-G maneuvers, the head and neck are subjected to a large increase in mechanical forces. When such high force loads on the head and neck exceed the ability of the muscles to maintain the position of the head, injury to the neck can result. The weight of the flight helmet compounds this problem. When the neck muscles become fatigued, the neck is at greater risk for injury. Neck injuries of various types most frequently occur in pilots flying the F-15, F-16, and F-18 (4,121,188). Also, the incidence of serious neck injuries is significantly increased in pilots 35 yrs. of age and older (188). Therefore, to prevent or minimize neck injury, a neck conditioning program is recommended that involves all neck muscle groups to increase their force generation capacity and to increase their time to fatigue. Such a program will significantly enhance the ability of the neck muscles to resist injury during high-G loading.

Specific recommendations concerning the prevention of neck injury during G maneuvers from a recent U.S. Air Force report are (188):

1. Perform neck exercises regularly to build up muscular strength.

2. Perform neck stretching warm-ups before high-G air combat maneuvers.

3. Cautiously return to high G after a long layoff from high-G flying.

4. Minimize neck movement under high-G loads.

5. Maintain good physical condition, nutrition and rest.

Program Interruptions

To minimize the effects of interruptions on an exercise program, these guidelines should be followed. The aircrew should arrange a schedule to obtain a minimum of 5 weeks of uninterrupted conditioning to begin a strength conditioning program. In this time, sufficient muscle-nerve adaptation will have occurred to initiate gains in muscular strength and endurance. During interruptions, the participant should continue the training program by whatever means available at least twice weekly to maintain previous gains. If standard exercise equipment is not available, the pilot should devote the exercise time to push-ups, sit-ups, leg raises, chair presses, back arches, neck flexion and extension movements, and isometric contractions of the major muscle groups. If the break in conditioning is 2 weeks or more, the participant should probably return to the conditioning program using 80-90% of the load employed during the conditioning session immediately before the interruption.

Maintenance Program

As stated earlier, completion of a 12-week strength and endurance exercise program should result in a 10-20% increase in strength and endurance. However, to maintain this fitness level, workouts must be continued with a combination of the different programs performed twice a week. The same workouts should not be performed on consecutive days and should represent a workout intensity equal to that performed when the program was completed.

Preflight/Pre-engagement Warm-up

Preparation for maximum G stress in an air combat engagement should include muscular warm-up and stretching. Before entering the aircraft, the aircrew should perform stretching movements of the trunk and neck rotations that might be integrated into the preflight check of the aircraft. The aircrew should perform neck stretching against resistance after becoming strapped into the aircraft seat during taxi or while waiting for takeoff. During airborne G-awareness turns, neck movements and an AGSM should be performed. These movements should simulate those anticipated during the aerial combat maneuvers. After exposure to these low G levels, the aircrew will be in an optimum condition to withstand high G when they enter an engagement.

AEROBIC CONDITIONING

A running (jogging) exercise performed for extended periods of time (20-30 min several times a week) will improve the function of the cardiovascular system. The intensity of the exercise should depend on the heart rate that should be kept in the "target range" during the conditioning. The target range is determined through calculation of the maximum rate (220 minus age) and multiplying by 60 and 80%. For example, a 20 year old has a calculated maximum heart rate of 200 (220 - 20) x 0.6 or 0.8 gives an exercise target range of 120-160 bpm.

A running program of 20-30 min, 3 times per week, is suggested as adequate for maintaining good cardiovascular fitness while avoiding the possible adverse effect of excessive aerobic training—discussed earlier in this chapter. A total of no more than 9 mi (14.5 km) of jogging per week is advised. If a pilot desires to run more than 9 mi, a flight surgeon should be consulted. A running exercise program should always be integrated with an anaerobic strength conditioning program; however, no scientific evidence shows that an excessive aerobic program can be counteracted, regarding its adverse G-tolerance effects, with a vigorous strength conditioning program. Persons unaccustomed to aerobic conditioning should begin the program by initially running a short distance at a slow pace. The time and distance of running should then progressively be increased, staying within the heart rate target range, until the desired level of aerobic conditioning is attained. Resting heart rate should stay above 55.

Other aerobic exercises such as rowing, cycling, swimming, cross-country skiing, aerobic dance, walking, etc., can be used as an alternative to running. These aerobic exercises should also be performed at an intensity that will achieve the "target" heart rate for at least 20-30 min. These exercises should be conducted with moderation.

LIFE-STYLE CONSIDERATIONS

Stressors

Life-style stressors can have a significant effect on G tolerance, e.g., illness, smoking, alcohol, medications, and just "every day" life problems can adversely affect G tolerance. Simply worrying about an argument that occurred earlier in the day can preoccupy the mind so that preparation for the AGSM is dangerously slowed by a sec or two. Illness and/or medications can interact with body processes in unpredictable ways in the flight environment. Aldaxacide and propranolol used for treating hypertension, do not significantly reduce G-level tolerance nor affect arterial pressure, although the increase in heart rate from the G exposure was significantly reduced in those individuals taking propranolol (IV 0.25 mg/kg body mass) (21,111). Flight surgeons should always be consulted on these matters.

Alcohol is known to adversely affect flight performance by significantly interfering with mental, physiologic and physical functions. Interestingly, alcohol reduces relaxed G-level tolerances only slightly. Drinking 4 ounces of whisky decreases relaxed tolerance by only 0.2 G. This modest effect is considered to be via a peripheral vasodilation. However, the major detrimental effect of alcohol is in impairing judgment and dexterity. Burton and Jaggers (43) measured proficiency of a target-tracking task before and one hr after drinking graded doses of ethyl alcohol. The effect of blood alcohol on reductions in performance were determined with the major change occurring in those subjects with 0.1% blood alcohol (i.e., considered legally drunk in most countries). At this level, performance was decreased about 40%--and when combined with acceleration, it was reduced further by 10% per G (so at 5 G, it was decreased a total of 90%). Therefore, it is generally accepted and for good reasons that aircrew be prohibited from drinking alcohol at a minimum of 12 h prior to flight. The idea is, of course, that aircrew should not fly under the influence of alcohol. However, the 12 h rule is not always enough, and recent experiments show that even if blood alcohol concentration is zero, aircrew performance can be deteriorated for 48 h after intake of large amounts of alcohol because of the "hangover." Dehydration (see following section), known to reduce G tolerance, is common the day following a night of excessive alcohol consumption.

The AGSM requires rapid movement of air through the lungs, therefore, cigarette smoking (known to increase airway resistance) should be kept to a minimum with complete abstinence advised. Also, smoking has been shown to increase the severity of acceleration atelectasis (27).

Hydration

The state of hydration is particularly important to aircrew of high performance aircraft if high-G missions are flown in hot conditions (see Chapter 3). The adverse effects of high thermal loading on G tolerances can be significantly reduced if hydration is maintained. Therefore, aircrew should maintain their state of hydration. To accomplish this, aircrew should prehydrate by consuming a minimum of half a liter of water before flying. Rehydration after flight should follow 1 liter of water per kg of body weight lost. The sensation of thirst is not an adequate indicator of dehydration; therefore, aircrew may be dehydrated without realizing it.

Nutrition

On occasion, especially before G-LOC was found to be a relatively common occurrence for fighter pilots (before 1980), the nutritional status of pilots was considered as a likely cause of accidents involving sudden incapacitations. Specifically, hypoglycemia was blamed, although an adverse effect of low blood sugar on high G tolerance had never been clearly documented (26). Relaxed G-level tolerance studies that measured the effects of hypoglycemia following insulin injections (26,57) have not been convincing. In one study (57), no changes in relaxed G tolerance were found with either hyperglycemia or hypoglycemia, whereas in the other study, Browne (26) reported a decrease in relaxed G-level tolerance of 0.6 G with hypoglycemia and an increase of 0.5 G above control levels during the reactive period of the hypoglycemia attack. These modest changes in G tolerance appear to follow arterial blood pressure changes associated with hypoglycemia. Brent et al (24) reported a synergistic decrease in G-level tolerance as measured with slowed EEG activity with a combination of hyperventilation and hypoglycemia.

Sources of energy for optimal athletic performance are enhanced by proper nutrition and physical conditioning. Energy stores available to the body are not primarily obtained from the preflight meal, but result from previous diet and activity patterns.

Contrary to popular belief, a diet high in protein is not essential to develop muscle strength during a conditioning program. Total calories are important to ensure that protein in the diet is available for purposes of muscle development and maintenance. About 50-60% of dietary calories should be derived from complex carbohydrates such as pasta, breads, and potatoes. Fruits and vegetables should always be prominent in the diet.

Summary

To perform at their best, aircrew must be well rested, in good physical condition, properly nourished, and sufficiently hydrated when beginning a mission. Adequate physical recovery and liquid replenishment must be planned and taken after each sortie involving high Gs, or after exercise.

SUMMARY

A physical conditioning program that increases the strength of the major muscle groups is considered useful to aircrew of high performance aircraft. Such a program increases tolerance to high G aerial combat maneuvers, where an anti-G straining maneuver (AGSM) is used, by reducing fatigue. Improvements of 3 to 53% in a simulated aerial combat maneuver duration-tolerance test following a 12-week weight-lifting program have been found in the laboratory. The energetics of the AGSM is anaerobic that directly relates to the energy basis of the aerial combat maneuvers. Therefore, a physical conditioning program that increases anaerobic capacity and power is also considered desirable to increase ACM tolerance. Excessive aerobic exercise is discouraged for pilots of high performance aircraft since it increases heart arrythmias and the incidence of G-LOC with slower recovery from G-LOC and increases the incidence of motion sickness. A maximum of 15 km jogging per week is recommended. Physical training concepts to develop a conditioning program for pilots are reviewed. The importance of such exercises to improve neck strength is acknowledged. Keeping life-style stressors at a minimum and using good nutrition are considered important in maintaining optimum daily high G tolerance. The current status of all NATO countries regarding their position on recommending or requiring physical conditioning programs for fighter pilots is reported.

CONDITION PHYSIQUE - CONSIDERATIONS PHYSIOLOGIQUES.

Un programme de mise en condition physique augmentant la force musculaire est utile pour les équipages d'avion de haute performance. Un tel programme augmente la tolérance des pilotes aux accélérations. Il réduit la fatigue observée lors de la manoeuvre anti-G. Une amélioration de 34 à 53 p. cent du temps de tolérance à des accélérations simulant le combat aérien a été observée à la suite d'un stage d'haltérophilie de douze semaines. La manoeuvre anti-G fait essentiellement appel à une activité anaérobie des muscles. Il s'ensuit qu'un programme de conditionnement physique de type anaérobie est nécessaire pour améliorer la tolérance des pilotes aux profils de combat aérien. Par contre, un conditionnement physique de type aérobie est contre-indiqué pour les pilotes d'avion à haute performance pour plusieurs raisons. Il augmente la survenue des arythmies cardiaques, favorise la survenue de pertes de connaissance sous accélération et ralentit la récupération psychomotrice qui fait suite à la perte de connaissance et enfin il augmente le mal des transports. Un maximum de 15 km de footing par semaine est recommandé. Quelques idées de base pour l'élaboration d'un programme de mise en condition physique à l'intention des pilotes sont examinées. La nécessité de muscler le cou est aussi reconnue. La réduction des stress et l'adoption d'une bonne nutrition sont considérées comme des facteurs importants du maintien d'une tolérance optimale aux accélérations +Gz. La position actuelle de chacun des pays membres de l'OTAN en ce qui concerne la recommandation ou l'imposition d'un programme de mise en condition physique pour les pilotes de chasse est présentée.

CHAPTER 8
CENTRIFUGE TRAINING

TRAINING OBJECTIVES

a. Primary. The primary objective of centrifuge training is an increase in G tolerance resulting from improved skill in performing an anti-G straining maneuver (AGSM) and familiarization in the use of high-G protective equipment.

b. Secondary. A better understanding of the physiologic mechanisms of G-stress and G-tolerance, the symptoms of G-stress, the aids to counteract G-forces and finally the factors influencing the personal limitations achieved during the training.

TRAINING CENTRIFUGE REQUIREMENTS

Fighter aircraft crew members should be trained in a safe environment suggesting a realistic cockpit arrangement and with a realistic flight control simulation (2, 84,89,179). Training centrifuges should preferably have an arm length of at least 6 meters and be capable of attaining +12 G_z with an onset rate of 6 G/sec from idling (see Chapter 6).

Further optimum requirements are:

1. An operator control panel with monitoring equipment, communication and safety system features
2. Safety and emergency stopping devices
3. A video monitoring and recording system
4. A communication system
5. A light-bar system for end point determination (see Chapter 3)
6. An anti-G air supply and valve system (see Chapter 3)
7. An automatic and a "pilot in the loop" flight control system
8. A realistic target tracking system with head-up display (HUD)
9. A (computer-generated) visual display system
10. Medical and physiological monitoring and recording equipment for EKG, heart rate, blood pressure, G-level, G-suit pressure, and positive pressure breathing under G (PBG).
11. A gondola resembling the cockpit environment of the pilots' aircraft type as far as possible (e.g., position of control stick, arm and feet rests and throttle; a pilot seat with correct seatback angle and correct positioning of torso and limbs)
12. A PBG regulation system
13. A "check six" mark
14. Emergency Medical Equipment and Drugs (Appendix C)

The specifications of anti-G and PBG systems should be the same as the aircraft systems.

G TRAINING METHOD

The method described in this chapter requires 1 duty day for training. Trainees must meet the medical standards required for flying high performance aircraft. Those suffering from medical conditions which may adversely affect high-G centrifuge training should be excluded until medically fit (179). Because there is an essential difference in the execution of the AGSM with or without equipment the pilots should use equipment such as flying helmet, oxygen mask and G-suit, that is specific to their aircraft type. There is however, disagreement about the use of an oxygen mask and helmet during G training between the USAF and the other NATO Air Forces. The U.S. Air Force in its training does not use them because they prevent the trainer from seeing the face of the trainee during G exposure. The trainer can obtain useful information about the effectiveness of the AGSM by observing the action of the trainee's facial muscles and mouth. Also the helmet adds weight to the head and increases the possibility of neck injuries during G induced loss of consciousness (G-LOC). The Air Standardization Coordinating Committee (ASCC) is considering an amendment to ASCC ADV PUB 61/51 "Centrifuge Training to Increase High-G Tolerance" that now restricts the use of a mask and helmet and will require the use of these during the last training ride that is a type of simulated aerial combat maneuver (SACM), profile five of the training profiles, see this Chapter.

The training is conducted by an experienced fighter pilot who has received sufficient training in physiology. A qualified physician is required to be available during the actual centrifuge training. Constant video and auditory contacts are made with the trainee during the training session. All training runs should be video recorded since these recordings are extremely valuable training aids. EKG and heartrate may be recorded for medical monitoring.

Prior to exposure to G the trainee will be briefed on the procedure involved and instructed how to perform a proper AGSM.

The centrifuge training profiles will be developed from the operational characteristics of the aircraft type the pilot will fly.

A centrifuge run may be terminated at any time by the trainee or by the supervisor. Recommended physiological criteria for terminating a run are severe motion sickness, nausea or vomiting, neck or back pain, and of course a G-induced loss of consciousness (G-LOC). The training may be continued after investigation of the problem. A G-LOC is no reason to discontinue the training indefinitely.

Trainees who do not successfully complete the training qualification profile may be required to repeat the training (see Chapter 9).

Pre-training and anonymous post-training questionnaires completed by every trainee will provide data for statistical use (see Appendix A and Appendix B).

It is advised that subjects trained in the centrifuge do not fly as crewmembers for 12 hours after the end of the training.

THEORETICAL TRAINING OF AIRCREW FLYING HIGH PERFORMANCE AIRCRAFT (HPA)

Theoretical training of aircrew should start with a briefing covering the high G-physiology (see Chapter 2). The immediate and delayed effects of increased G on the body including blood pressure drop at brain and eye level, resulting in peripheral light loss (PLL), central light loss (CLL), tunnel vision, grayout, blackout, and G-LOC should be discussed. The G time tolerance curve (see Chapter 3) can be used to explain these effects with different G onset rates and times. It should be emphasized that a G-LOC followed by a period of confusion and disorientation can incapacitate a pilot for such a time that loss of life and aircraft may occur.

The physiological and mechanical protection methods that can be used, such as the AGSM, Anti-G suit, positive pressure breathing under G (if installed in the aircraft), and body position should be briefed, as well as the importance of a good physical condition.

Special attention should be given to the proper execution of this maneuver (see Chapter 3) as the AGSM is at the present the most effective aid to counter the effects of $+G_z$ on the human body. All aspects, such as muscle tensing of arms, legs, abdomen, and the cyclic increase of intrathoracic pressure for about 3 to 4 seconds should be covered in detail. As the execution of the AGSM is rapidly causing fatigue, influencing the G tolerance, the use of this technique should be limited to a level which enables the pilot to do the job. A video demonstration of a poor and a well performed AGSM is very useful.

The layout of the centrifuge gondola, position and operation of switches, indicators, and handles should be briefed as well as the training profiles to be flown.

After the centrifuge training, the performance of each trainee should be evaluated using the video tape recordings. In case of a particular instruction event such as a G-LOC, special attention should be given to this event.

Factors affecting a pilot's G tolerance should be discussed. The most important factors are the execution of the AGSM, G-suit fitting, fatigue, heat, dehydration, and physical condition.

The overall results of the training must be discussed and the post-training questionnaire must be completed to gain full benefit from the training.

TRAINING PROFILES

The primary aim of centrifuge G training is to teach aircrew how to perform an effective AGSM under actual G and with high onset rates. The program should consist of five more or less standard profiles; the training qualification profile and the simulated air combat maneuvering profile should be developed from the operational characteristics of the aircraft type the trainee will fly.

The following profiles are given as an example for training pilots flying or earmarked to fly the F-16. If training aircrew flying aircraft equipped with a more inclined seat, the maximum G_z values in profiles 2, 3, 4, and 5 must be lowered by 1 G_z.

A rest period of at least 2 minutes between profiles is required. During this period the trainee can be debriefed on his performance. Trainees should monitor the training of their colleagues.

Profile Number One: Relaxed G-tolerance Profile

This gradual onset run (GOR) is controlled by the computer so that the trainee can concentrate on the AGSM. The G-suit is not pressurized, and the trainee is wearing a lightweight headset so the supervisor can visually monitor the performance of the AGSM and give instructions, if necessary.

The pilot relaxes at the onset of G and concentrates on the red light of the light bar-system (see Chapter 3) or a mark on the twelve o'clock position. As visual cues are experienced with disappearance of the green lights, the pilot starts to perform the AGSM until visual cues are experienced again or +9 G_z is reached. In both cases, the centrifuge will decelerate. Trainees should be warned to keep straining until the centrifuge reaches a low $+G_z$ level, which can take several seconds. This procedure is followed to prevent a G-LOC due to premature relaxation.

The difference in G_z-level, between straining and not straining, is an indication of the effectiveness of the AGSM.

Profile Number Two: Practice Profile.

In this rapid-onset run (ROR) profile the trainee tracks a computer-controlled target at 6 G_z for 30 seconds. The G-suit is working, and the helmet and oxygen mask are the trainee's assigned equipment.

Fig. 8-1
Relaxed G Tolerance Profile.

The AGSM should be started prior to reaching 6 G_z, or sooner when necessary. This profile gives the trainee the opportunity to practice target tracking and to perfect the AGSM. In case the trainee did not perform an effective AGSM in profile number one, profile number two may be preceded by a computer-controlled ROR profile to 6 G_z for 30 seconds, giving the supervisor more time to instruct the trainee on the execution of the AGSM.

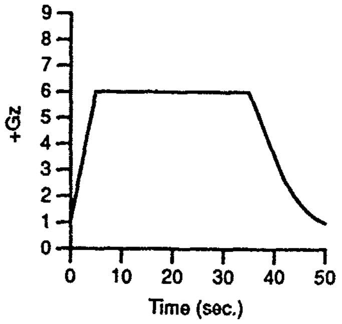


Fig. 8-2
Practice Profile.

Profile Number Three: Qualification Profile

In this very rapid onset run (VROR) profile the trainee tracks a computer-controlled target at 8 G_z for 15 seconds. The G-suit is working and the helmet and oxygen mask are the trainee's assigned equipment. The AGSM should be started at the onset of G.

Pilots flying F-16 aircraft should be capable of completing this run, demonstrating their performance in executing a good AGSM.

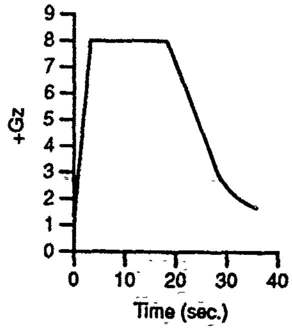


Fig. 8-3
Qualification Profile.

Profile Number Four: "Check Six" Profile

This VROR profile is computer controlled; the trainee initiates the run by pulling the stick bringing the G_z level up to 9 for 15 seconds. The G-suit is working and the helmet and oxygen mask are the trainee's assigned equipment. At the start of the run the pilot looks over the left shoulder to a check 6 mark on the "seven o'clock high" position and immediately thereafter initiates the run and starts the AGSM.

This profile gives the trainee the opportunity to perform the AGSM in a non optimal body position.

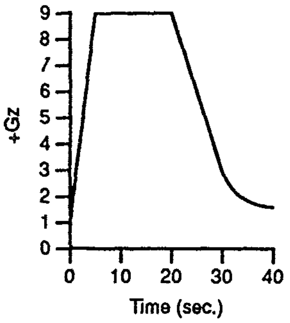


Fig. 8-4
Check Six Profile.

Profile Number Five: Simulated Aerial Combat Maneuvering (SACM) Profile (optional)

In this VROR/SACM profile the trainee tracks a computer-controlled target to a 9 G_z peak for 10 seconds, then back to a 4 G_z plateau for 10 seconds followed by a second peak of 8.5 G_z for 15 seconds. The G-suit is working, and the helmet and oxygen mask are the trainee's assigned equipment.

The AGSM should be started with the onset of G to both peaks. This profile gives the trainee the opportunity to practice the AGSM under more realistic conditions. Because of rapid buildup of fatigue, some trainees may be too tired to fly this profile.

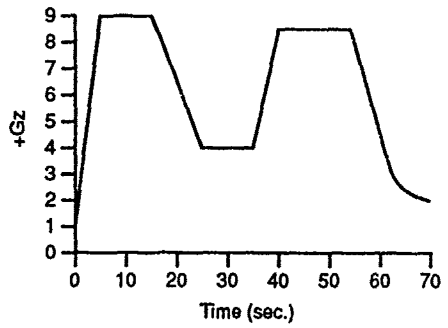


Fig. 8-5
Simulated Air Combat Maneuvering Profile.

SUMMARY

G training of aircrew flying high performance aircraft up to high G levels with high onset rates is necessary. Centrifuge training offers the opportunity to accomplish this training in a safe environment. The gondola layout and G characteristics of training centrifuges should make a realistic G training possible.

Theoretical training must cover the aspects of body response to $+G_z$ and the aids available to minimize the adverse effects. The danger of G-LOC should be stressed. Appropriate profiles are described.

The AGSM is presently the most important aid to sustain high G levels and high G-onset rates. Pilots should therefore be thoroughly capable of performing this maneuver correctly and efficiently. A number of profiles should be flown on the centrifuge to teach trainees the perfect AGSM and show them the improvement in G-level that can be achieved.

ENTRAINEMENT EN CENTRIFUGEUSE.

L'entraînement en centrifugeuse des équipages d'avion à haute performance soumis à des facteurs de charges élevés et à des vitesses de mise en accélération très importantes est indispensable. La centrifugeuse offre l'environnement le plus sûr pour cet entraînement. Les caractéristiques et les équipements techniques de la centrifugeuse doivent permettre la réalisation d'un entraînement réaliste. La partie théorique de cet entraînement doit couvrir les différents aspects de la réponse physiologique aux accélérations +Gz et les moyens de protection anti-G qui minimisent les effets néfastes de ces accélérations. Les profils d'entraînement en centrifugeuse sont présentés. Les risques de perte de connaissance doivent être soulignés. A l'heure actuelle, la manoeuvre anti-G représente le moyen le plus efficace contre les accélérations élevées et rapidement installées. Par conséquent, les pilotes doivent être entraînés à cette manoeuvre et doivent l'exécuter correctement. Les pilotes doivent être soumis à plusieurs profils d'accélération en centrifugeuse pour qu'ils effectuent parfaitement cette manoeuvre et qu'ils comprennent le gain de tolérance qu'elle apporte.

APPENDIX A

PRE-TRAINING QUESTIONNAIRE

1. Last name: First name:
2. Birth date: Weight:
3. Height:
4. Aircraft types you have been flying and flying hours in these aircraft.
5. Number of sorties in the last 30 days.
6. Number of days since last sortie.
7. Aerobic training (running, swimming, cycling, etc)
   a. How many times per week do you exercise?
   b. How long is your average workout?
8. Anaerobic training (weight lifting)
   a. How many times per week do you exercise?
   b. How long is your average workout?
9. What is the maximum G-level you think you can tolerate for 10 seconds and still be functional (fly the aircraft and spot other aircraft)?

APPENDIX B

ANONYMOUS POST-TRAINING QUESTIONNAIRE

1. High G training has specific objectives; some of them are listed below. Please give us your idea how well we have managed to communicate these objectives.

Objectives met: yes / no / partially

2. Increase your knowledge about the physiology of G stress, the hazards of high G levels and onset rates and the ways to protect you against these hazards.

3. Teach you to perform an effective anti G straining maneuver.

4. Improve your confidence to be able to sustain high G levels and onset rates.

5. Improve flying safety and combat effectiveness

6. Do you think regular centrifuge training is necessary for aircrew flying high performance aircraft, and if so, how often?

7. During your flight career have you ever experienced a G-LOC? Please briefly describe the incident; e.g. (a) what maneuver; (b) when during the ACM; (c) why did it happen (your thoughts); (d) how many seconds was the aircraft out of control (your estimations), etc.

APPENDIX C

ADVISED MEDICAL EQUIPMENT AND DRUGS FOR CENTRIFUGE TRAINING

Portable ECG monitor and defibrillator
Portable O_2 supply with masks & connectors for endotracheal tube connection
Oropharyngeal airways
Endotracheal tubes and laryngoscope with blades
Ambu bag with masks
Portable suction machine
I.V. tubing and appropriate sized catheters
Needles, syringes, and I.V. stand
C-Spine collars
Blood pressure cuff, stethoscope, and small flashlight

Medication	Strength	Unit
Atropine Sulfate	0.1 mg/ml	10 ml
Bretylium Tosylate	50 mg/ml	10 ml
Calcium Chloride 10%	100 mg/ml	10 ml
Dopamine HCL	40 mg/ml	5 ml
Epinephrine 1:10,000	0.1 mg/ml	10 ml
Isoproterenol HCL	0.2 mg/ml	5 ml
Lidocaine HCL 1%	10 mg/ml	10 ml
Lidocaine HCL 4%	40 mg/ml	25 ml
Procainamide HCI	100 mg/ml	10 ml
Procainamide HCI	500 mg/ml	2 ml
Sodium Bicarbonate 7.5%	75 mg/ml	50 ml
Verapamil HCL	2.5 mg/ml	2 ml
Aminophylline	25 mg/ml	10 ml
Diazepam	5 mg/ml	2 ml
Hydralazine	20 mg/ml	1 ml
Morphine Sulphate	2 mg/ml	10 ml
Phenytoin Sodium	50 mg/ml	5 ml
Salbutamol inhaler		
Dextrose 5% (D5W)	250 ml	
Sodium Chloride 0.9% (N/S)	250 ml	

As can be readily seen, most of the drugs are for cardiac arrhythmias

CHAPTER 9
TRAINING APPLICATIONS AND STANDARDS

Preceding chapters have clearly shown the benefits of centrifuge G training. However, since the cost and time requirements for such training are significant, standards should be established for the following factors: selection of pilots for centrifuge G training, scheduling of training, required G levels, and frequency of retraining, if required. Since not all pilots of all types of aircraft that can develop G can be centrifuge trained whenever they desire, limitations based on relevant facts must be developed and, if necessary, prioritized relative to their importance. This approach means that even though we try our best, some pilots who do need G training will not receive it. Some pilots exposed to 3 G will experience G-induced loss of consciousness (G-LOC), but not all pilots exposed to such low G levels will be allowed to receive centrifuge training. Hence, we have developed training standards based on the best compromises possible guided by the most current information available. However, these standards should not become stagnated, but should be reviewed and modified based on new information.

We are also cognizant that each nation has its own pilot selection and training procedures and regulations that will make it impossible for every nation to adhere to the standards prescribed herein. Certainly each nation has its own goals and priorities regarding defense and for good reasons—a chapter in an AGARDograph will not change these.

SELECTION OF PILOTS FOR CENTRIFUGE G TRAINING

The centrifuge G training is primarily directed towards teaching aircrew how to perform an effective anti-G straining maneuver (AGSM). Undoubtedly, additional benefits are derived from centrifuge training, such as learning one's G tolerances, experiencing G under controlled conditions, and even perhaps losing consciousness. Interestingly, there is some evidence that exposure to G-LOC on the centrifuge is beneficial relative to better recognition when it occurs in an aircraft by accident (so that the pilot knows it has happened) and more rapid recovery (see Chapter 5) (32,203).

However, if we restrict centrifuge G training and use it for its primary purpose, those pilots exposed to: (a) 4 G and above who are not using an anti-G suit; and (b) 5 G and greater if an anti-G suit is in use, should receive centrifuge training. The basis for these G levels is that the AGSM is required for the mean population when these G levels are exceeded (see Chapter 3). However, it has been clearly established that G-LOC can occur in pilots exposed to G levels less than 4 G (60,199). Fortunately, these episodes have generally occurred in two-seat trainer aircraft so that one person was conscious and able to maintain control of the aircraft.

If positive pressure breathing for G protection (PBG) (see Chapter 4) becomes operational and if G training in its use is considered important in gaining its maximum benefits, then centrifuge PBG training will be essential.

SCHEDULING OF TRAINING

Adequate training to protect against hazardous environments should be provided before exposure to such environments. Centrifuge G training should not be an exception, so pilots who will be exposed to increased G levels should be trained before they have reached these G levels inflight.

TRAINING REQUIREMENTS

The development of a G tolerance requirement clearly establishes a pilot selection criterion and, therefore, by definition, if these requirements are to be recognized by a nation, pilot selection for G tolerance training has begun. Clearly, the issue is more than simply centrifuge G training. For some nations, such a pilot selection process may be questioned for several reasons. We will therefore not even begin to address the thorny issue of pilot selection for G tolerance. What follows, however, is a reasonable approach in the determination of G-tolerance goals that make sense.

Since the G environment has both G-level and G-duration dimensions, the standards governing training requirements must include G level as well as time at G. These training standards, since they involve safety, should be developed as safety regulations are developed. Usually, safety standards cover all possibilities and include an extra safety margin. Engineers generally use a safety margin of 50% to insure that systems failure will not occur due to some miscalculations, structural fatigue, extra stresses, and perhaps some faulty construction. We perhaps should attempt to do likewise here for G training to demonstrate, if for no other reason, that our current G protective systems are inadequate (see Chapter 3). If this approach (let's use only a 10% safety margin) was to be applied to G training, then the pilot would be capable of tolerating one G more than the maximum capability of their aircraft. Pilots of high-performance jet trainers that are capable of 5 G that do not accommodate an anti-G suit, should demonstrate at least 6 G for 15 sec tolerance without using an anti-G suit. Since the F-16 is limited to 9 G and can theoretically sustain that for several minutes, we should have pilots trained to tolerate 10 G (which includes the 10% safety factor) for several minutes. However, with inadequate operational G protection systems to consider (see Chapter 3), and since the aircraft capabilities are controlled by pilots (who know their G tolerance capabilities—particularly if they have had centrifuge G training), we will not be able to (nor hopefully need to) apply a safety factor when training for the most agile fighter.

We, therefore, will use G levels and durations that are based solely on the pilot population capabilities using standard operational G-protection methods. It is impossible to base these G-tolerance standards on the hard logic that pilots should be capable of outperforming their aircraft. The standards suggested herein are based on reason, centrifuge training experience, and some educated guesswork.

The AGSM, if performed maximally, should increase G tolerance by 4 G. Using the anti-G suit that increased G tolerance by at least 1 G, a pilot with a mean relaxed rapid onset run (ROR) tolerance of 4 G should be capable of tolerating 9 G—the capability of most modern high performance aircraft. The recent experiences of the United States (U.S.) in pilot high-G centrifuge training shows that in fact a 9 G, 15 sec, G training goal was attained by 94.1% of the pilot trainees. The "check six" 9 G for 10 sec run was accomplished by 93.4% (89). Therefore, it is not unreasonable to expect all pilots flying fighter aircraft that are capable of 9 G, to withstand 9 G. Using this standard of 9 G for 15 sec, about 6% of the pilot population would fail.

This discussed G tolerance level of 9 G for 15 sec is 2 G higher than the NATO definition of High Sustained G (HSG) as stated in Standard (STANAG 3827 AMD), Recommended Requirements for Training of Aircrew in High Sustained "G" Environments, and the Air Standardization Coordinating Committee (ASCC, ADV PUB 61/26A) Standardized Centrifuge G-Stress Profiles for Medical Evaluation of Aircrew Members that recommend 7 G for 15 sec (1,179). More than 99% of the pilots who were trained in the U.S. were able to achieve this standard (89). Undoubtedly, such low G standards were proposed to evade the pilot selection issue.

Gillingham (85,89) has on numerous occasions supported the concept of selecting pilots for G tolerance. Of course, the questions remain: How do you test them? At what level of G tolerance should they be considered successful? A G tolerance level less than 9 G for 15 sec, as discussed herein, is difficult to rationalize. As Gillingham (85) states (no doubt with tongue in cheek) "... a G–tolerance standard of +7 G_z for 15 sec would certainly not be overly stringent ..." However, such a tolerance criterion can be considered significantly less than stringent. It is difficult to argue that the pilot should be capable of tolerating the levels of G capabilities of the aircraft and demonstrating that capability on a centrifuge following adequate training. To demand less is unconscionable. Although NATO Air Forces do adhere to the NATO STANAG (i.e., 7 G for 15 sec) as a minimum G standard, their training goal is 9 G for 15 sec in the F-16 configured seat. Failure to complete an 8 G 15 sec run in the F-16 seat results in vigorous retraining, physical conditioning, and reexposure until the 8 G, 15 sec run is successfully completed (i.e., as suggested earlier in this chapter, it is a *de facto* tolerance standard) (86).

If pilot selection for superior G tolerance is to be considered seriously, some testing procedure will have to be developed. How would such a test be devised? It has been clearly demonstrated that relaxed G tolerances are not highly correlated with high-G tolerances when the AGSM is required (Fig. 3-4). To measure high G tolerances that required the AGSM, the selection process would require that all potential pilot selectees would have to be trained in performing the AGSM to measure that high G capability. Such a procedure requires a centrifuge and time for AGSM training, and therefore is not usually practical in selecting pilots—a process that should be accomplished within one or two days. At present, one test that appears to be potentially useful in such a selection process can be done quickly and does not require a centrifuge. The Wingate Test indirectly measures the AGSM capability of a selectee by testing his anaerobic power capability and has been shown to be highly correlated with the maximum AGSM capability of highly trained male subjects (196, Chapter 7).

G - TRAINING FAILURE

What then should be the disposition of those trainees who cannot meet G training standards—whatever those standards might be? This problem has been adequately addressed by Gillingham (85) and will be summarized here.

1. Retest on another day as soon as possible to take advantage of the prior centrifuge training. A maximum of 3 test days (periods) should be allowed.

2. If retesting fails, then the student should be evaluated medically.

3. If medically qualified but considered having inadequate muscular strength and anaerobic capacity (as measured using the Wingate Test), then a 1 to 2 month prescribed intense strength conditioning program should be initiated (see Chapter 7). Upon its completion, the student should be retested.

4. Continued failure at retesting should lead to recommendations that the student (or pilot) should be limited to flying tanker and transport aircraft. The pilot should not be permitted to fly fighter, attack, reconnaissance, or even certain types of bomber aircraft with G capabilities greater than 5 G for 4 seconds.

PILOT CENTRIFUGE RETRAINING

Should pilots who have successfully "passed" centrifuge G training one time be required to routinely repeat that training at prescribed time intervals? If not, should these pilots ever have to be retrained; e.g., following an illness or perhaps after a tour of duty that did not include flying high G? As for all of the issues addressed in this chapter, there are no ready answers. This issue was recently addressed (1 Feb 89) at a U.S. Air Force Joint Working Group on High-G Refresher Training. The conclusion from this meeting was "... that there was insufficient information available to the working group to determine whether or not centrifuge-based G refresher training would be effective." Efforts are underway to obtain additional pertinent information.

The Netherlands centrifuge G training program has had experience with 5 Dutch pilots who were retrained one to three and a half years after receiving their initial centrifuge training. At the time of their "retraining," these pilots had been routinely flying F-5 and F-16 aircraft. Four of these pilots performed well, and one performed slightly below average. From this limited information, it appears that routine retraining of pilots on the centrifuge would not be cost effective (Hoekstra, personal communication).

Although information is not sufficient to set conclusive standards, the following recommendations regarding the need to retrain on the centrifuge are offered:

1. Nonflying periods that exceed 6 months or following a nonflying extended tour (2-3 years) of duty.
2. Medical problems that require grounding for 1 month or more. Particularly if retraining was recommended by a flight surgeon.
3. Transitioning a pilot from a low-G to a high-G aircraft.
4. A centrifuge-trained pilot requests G training.
5. Routine repeat training every 5-6 years and perhaps incorporated in the routine physiological retraining program for hypoxia and rapid decompression. This training for NATO (STANAG 3116) is every 3 years so that repeated centrifuge training would most efficiently be included during this training cycle; i.e., every 3 years or perhaps every 6 years.

The benefit from receiving controlled G exposures after some periods of time without G exposure because of nonflying or a medical condition (i.e., readapting to the high-G environment, see Chapter 3) is probably as important as the AGSM training. Perhaps a check ride to determine the AGSM capability of the pilot might be useful relative to the first two recommendations.

SUMMARY

Standards for centrifuge G training are proposed that are based on reason, experience, and some educated guesswork. Centrifuge G training is used primarily to teach the anti-G straining maneuver (AGSM). Students should be centrifuge trained before they experience in-flight accelerations of 4 G and greater (without an anti-G suit) and 5 G and above with an anti-G suit. G-level/duration training goals for pilots of trainers should be G levels at least 1 G higher than the capability of the aircraft—with or without the use of the anti-G suit depending on the configuration of the aircraft. Goals for pilots of high performance aircraft should be 9 G for 15 sec with an anti-G suit. The widely accepted G training standard of 7 G for 15 sec is considered too low. Failure to achieve training goals would prevent a student from continuing pilot training. Familiarization PBG training on the centrifuge is considered essential. Retesting, medical examination, and/or improved physical strength conditioning are recommended for students who fail. Retraining of pilots who had initially passed centrifuge training is recommended if they had not flown for 6 months or had medical problems that grounded them for 1 month. Certainly, repeated G training is recommended if the pilot or a flight surgeon requested it. Routine repeated centrifuge training every 3 or 6 years was considered reasonable.

NORMES ET REGLES CONCERNANT L'ENTRAINEMENT

Les normes présentées ci-dessous sont fondées sur l'expérience, le bon sens et un certain nombre d'hypothèses justifiées. L'entraînement en centrifugeuse sert principalement à enseigner la manoeuvre anti-G. Les stagiaires doivent être entraînés avant toute exposition à des vols dont les accélérations dépasseront 4 G s'ils n'ont pas de pantalon anti-G, ou 5 G s' ils ont un pantalon anti-G. Les pilotes d'avion d'entraînement, devront être capables de tolérer une accélération de 1 G au-dessus de l'accélération maximale de l'avion. Pour les avions à haute performance, les pilotes équipés de pantalon anti-G devraient être capables de tolérer 9 G pendant une durée de 15 secondes. La norme largement admise de tolérance à 7 G pendant 15 secondes est trop basse. Il est recommandé que tout stagiaire incapable de respecter ces normes soit retiré de sa formation aéronautique. Si les pilotes doivent utiliser la surpression respiratoire comme moyen de protection anti-G, ils doivent être familiarisés en centrifugeuse avec cet équipement avant tout vol réel. Pour les pilotes qui ont été incapables de respecter ces normes, il est suggéré qu'un nouvel entraînement en centrifugeuse, et/ou un bilan médical, et/ou une mise en condition physique soient menés. Un nouvel entraînement en centrifugeuse est conseillé pour les pilotes qui n'ont pas volé pendant six mois ou qui ont été mis inaptes pour raison médicale pendant un mois. Tout nouvel entraînement doit être mené à la demande du médecin du personnel navigant. Un cours de réactualisation des connaissances tous les 3 ou 6 ans est considéré comme raisonnable.

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14. Abstract

High-G physiological protection training is currently of importance to NATO Air Force operations because of a deficiency in g protection methods. This deficiency can, and on occasion does, result in G-induced loss of consciousness (G-LOG) (Chapter 1). Consequently, these methods are supported and supplemented by increasing their effectiveness through: (a) increased understanding of the physiologic basis of G protection (Chapters 2 and 3); (b) development of advanced G protection concepts (Chapter 4); (c) knowledge of the system and basis of G-LOC (Chapter 5); (d) identification of the existence and location of human use centrifuges in NATO countries (Chapter 6); (e) increased physical conditioning (Chapter 7); (f) improved training of pilots on the centrifuge (Chapter 8); and (g) establishment of training goals and standards (Chapter 9). These topics are addressed at a scientific or technical level of knowledge that is possessed by everyone involved in acceleration research, G training, flying, or designing and building high performance aircraft. At the end of each chapter is a brief summary in both English and French.

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