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THE EXPERIMENTAL DIVING UNIT  
NAVY YARD, WASHINGTON, D. C.

and

NAVAL MEDICAL RESEARCH INSTITUTE  
NATIONAL NAVAL MEDICAL CENTER  
BETHESDA, MARYLAND

PHYSIOLOGIC FACTORS UNDERLYING THE PREVENTION  
AND TREATMENT OF DECOMPRESSION SICKNESS

Research Project X-443

Report No. 1

Approved for public release; distribution unlimited.

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PHYSIOLOGIC FACTORS UNDERLYING THE PREVENTION  
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A Procedure for the Treatment of Caisson Disease and  
Traumatic Air Embolism

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OBJECT

To develop a simple, comprehensive outline for the treatment of caisson disease and traumatic air embolism.

SUMMARY AND CONCLUSIONS

1. Twenty-seven first class divers and six pharmacist's mates undergoing training for qualification as second class divers participated in the various tests.
2. To test the treatment tables, divers were exposed to a one-hour work dive at 130 feet, and then one hour following decompression, recompression was applied according to the particular treatment table under study. In some instances the period on the surface between the dive and the treatment was decreased to thirty minutes. Although the divers seldom developed bends after the work dive, nitrogen apparently was present in the tissues in a state of supersaturation or in the form of minute bubbles. Thus, a second exposure, i.e., treatment, one hour after the work dive was usually followed by bends unless the decompression was prolonged. The decompression time required to prevent bends formed the basis for the treatment tables.
3. The following features are incorporated in the final treatment procedures formulated on the basis of tests of ten individual tables.

a. A thirty minute to two hour period at maximal pressure in order to insure relief of symptoms.

b. The application of maximal pressure followed by prolonged recompression at the 30-foot depth when symptoms are indicative of involvement of the cardiorespiratory and central nervous systems.

c. The use of oxygen.

d. Prolonged recompression for periods of eighteen to thirty-eight hours for serious cases, and

e. The treatment of traumatic air embolism by the application of maximal pressure followed by the breathing of oxygen at the 60, 50, and 40 foot depths.

## INTRODUCTION

Recompression has long been accepted as the only effective method of treating caisson disease. However, opinions as to the amount of pressure to be used and the time to be spent at various levels in the subsequent decompression have been quite diverse. Behnke and Shaw (1) elucidated the basic principles underlying recompression as a therapeutic procedure and outlined a method of using oxygen. Utilizing oxygen in conjunction with recompression. Yarbrough and Behnke (2) reported the successful treatment of 48 of 50 men with caisson disease which occurred after exposure in high pressure helium-oxygen atmospheres. The procedures described by these investigators have been used in repeated treatments in experimental diving and salvage operations with success. In most instances the cases were helium and oxygen "bends".

In order to provide personnel in the field with a simplified method of treatment for caisson disease when the services of a medical officer might not be available, a procedure was formulated and published in the Bumed News Letter in May 1944 (3). Reports from the field and experience at the Experimental Diving Unit showed that the use either of this treatment table or of the air treatment table appearing in the Diving Manual (4) was followed by recurrence of symptoms in about 50 per cent of the individuals treated. In order to verify field reports and to formulate adequate and comprehensive tables for the treatment of caisson disease and air embolism, a series of tests was performed at the Naval Medical Research Institute and at the Experimental Diving Unit.

## PROCEDURE

Thirty-three enlisted men from 19 to 30 years of age and of body specific gravity (5) from 1.102 to 1.046 were subjects (Table 1). Twenty-seven of the subjects were first class divers and six were pharmacist's mates undergoing treatment for qualification as second class divers.

The men, wearing standard navy diving dress and a 50-pound belt, dived in pairs, starting at 0830 each morning. They were placed in a diving tank in 7 feet of water and the air pressure above the water was increased until a simulated depth of 130 feet was reached.\* The water temperature in the various tests ranged from 38° to 54°F. (average 45°F). When "on the bottom" each subject lifted a section of pipe weighing 60 pounds in water from a bench 26 inches high to the floor level and back to the bench, ten times each minute for fifty-five minutes. The subjects were allowed to do the lifting as fast or as slowly as desired, provided that the task was accomplished in one minute. This work dive was terminated in one hour by decompression according to standard navy decompression tables (6). Thus, for a

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\*All pressures are given in feet of sea water. A pressure of one atmosphere (14.7 lb. per sq. in.) is equivalent to 33 feet of sea water.

dive of sixty minutes' duration at 130 feet, thirteen minutes were spent at 30 feet, twenty-eight minutes at 20 feet, and twenty-eight minutes at 10 feet. The first stop, at 30 feet, was spent in the water in the wet tank. At the start of the second stop, at 20 feet, the subjects were removed from the wet tank and decompression was completed in a dry chamber. At no time during decompression did the pressure drop below that prescribed by the decompression table. One hour or, in some cases, thirty minutes after surfacing from the wet dive, the subjects were exposed to the pressures of the treatment table undergoing test.

A standard navy recompression chamber was used for the tests of the treatment tables. The subjects, in pairs, remained in the chamber throughout the test period at rest sitting on chairs, playing games and reading, or lying down asleep. When oxygen was breathed the men were at complete rest recumbent. Humidified oxygen was breathed through a carefully fitted A-14 oxygen mask from a demand system. Analysis of gas samples withdrawn from the masks indicated that the oxygen concentration did not fall below 95 per cent. The chamber was ventilated every ten minutes for a period of one minute to prevent the accumulation of carbon dioxide in the chamber air and to remove excess ambient oxygen in order to minimize fire hazards. In tests of the treatment tables the divers were compressed at a rate of 25 feet per minute and during decompression one minute elapsed between stops.

The purpose of a work dive prior to the application of the treatment table was to saturate the body tissues with nitrogen to such degree that a second exposure unless followed by prolonged decompression would be certain to produce bends. For example, following a work dive, the application of the treatment decompression outlined in the table published in the Bumed News Letter (3) gave rise to bends in six out of ten individuals and it was necessary to recompress three of the men in order to alleviate symptoms. When the treatment table, however, was modified to include an additional hour of decompression, no symptoms developed. This illustrates the critical nature of the time factor that separates safe treatment from treatment that is inadequate.

The failure of bends to develop following the application of the second or "treatment" decompression was, therefore, the criterion used to determine adequacy of treatment.

#### EXPERIMENTAL DATA

Tests of the Bumed News Letter 165-foot air-oxygen treatment table.-  
This table provides for the following treatment for patients whose only symptom is pain:

Depth (feet of sea water)	165	140	120	100	80	60	50	40	To surface
Time at depth (minutes)	30	12	12	12	12	30*	30*	30*	5*

\*Breathing oxygen.

Ten subjects were exposed to the pressures of the table one hour after the wet dive. Three subjects (Abe, Mey, Cum) developed joint pain requiring recompression for relief after completion of the treatment table. Three subjects (Pac, Sim, Bun) had mild pain lasting fifteen to twenty minutes but recompression was not necessary to relieve the pain (table IIa). This test confirmed the field reports that the 165-foot treatment table was not entirely satisfactory.

Tests of modifications of the Bumeds News Letter 165-foot treatment table.- In an attempt to rectify the apparent inadequacies of the table, an additional thirty minutes of oxygen breathing was added at 30 feet according to the following table:

Depth (feet of sea water)	165	140	120	100	80	60	50	40	30	To surface
Time at depth (minutes)	30	12	12	12	12	30*	30*	30*	30*	5*

\*Breathing oxygen.

One of the two divers subjected to this modified table developed joint pain requiring recompression after surfacing (table IIb). These findings indicated that the table as modified was not satisfactory.

The addition of sixty minutes of oxygen breathing at 30 feet was required to make the table effective:

Depth (feet of sea water)	165	140	120	100	80	60	50	40	30	To surface
Time at depth (minutes)	30	12	12	12	12	30*	30*	30*	60*	5*

\*Breathing oxygen.

Following the work dive three men (Kos, Kra, and Kes) developed bends within a period of one hour after decompression. To these three and the remaining eight men performing the work dive, the above outlined table of recompression was applied. Bends did not develop or recur subsequently (table IIc). There were no symptoms indicative of oxygen poisoning.

Tests of 165-foot air treatment tables.- The following modification of the air treatment table of the Bumeds News Letter was tested:

Depth (feet of sea water)	165	140	120	100	80	60	50	40	30	20	10
Time at depth (minutes)	30	12	12	12	12	30	30	30	240	120	120

Two subjects exposed to the pressure of this table one hour after the 130-foot dive and four subjects exposed thirty minutes after the dive complained of fatigue following the test (tables IIId and IIe).

The table was further modified as follows:

Depth (feet of sea water)	165	140	120	100	80	60	50	40	30	20	10
Time at depth (minutes)	30	12	12	12	12	30	30	30	120	120	240

Two subjects were exposed to the pressures of this table one hour after the 130-foot dive and four subjects thirty minutes after the dive. All the subjects remained completely asymptomatic (tables IIIf and IIg).

Tests of a 100-foot air-oxygen treatment table.— The following table, developed by Yarbrough and Behnke (2) and Behnke (7), was tested:

Depth (feet of sea water)	100	80	60	50	40	To surface
Time of depth (minutes)	30	12	30*	30*	30*	5*

\*Breathing oxygen.

Tests were performed under two conditions: (a) one hour after exposure to the usual 130-foot dive and (b) thirty minutes after the 130-foot dive. None of twelve subjects exposed to the pressures of this treatment table thirty minutes after the wet dive developed symptoms of caisson disease (table IIh). Twelve subjects remained asymptomatic after exposure to the pressures of this treatment table one hour after the 130-foot dive (table IIIi). This table was considered to be satisfactory.

Tests of a 100-foot air treatment table.— The following 100-foot air treatment table, a modification of the 150-foot air treatment table of the Diving Manual (7), was devised:

Depth (feet of sea water)	100	80	60	50	40	30	20	10
Time at depth (minutes)	30	12	30	30	30	60	60	120

The table was tested under two conditions: (a) thirty minutes after exposure to the usual 130-foot dive and (b) one hour after the 130-foot dive. None of eight subjects had symptoms of caisson disease following exposure to the

pressure of the treatment table thirty minutes after the wet dive (table IIj). All three subjects were asymptomatic after exposure to the treatment table one hour after the wet dive (table IIk). This table was also considered to be satisfactory.

Tests of treatment tables providing for prolonged recompression.- The following table was tested without a preceding 130-foot dive:

Depth (feet of sea water)	165	140	120	100	80	60	50	40	30	20	10
Time at depth (minutes)	120	12	12	12	12	120* 22hr	120	120	120	120	120

\*Breathing oxygen.

Six subjects were exposed to the pressures of this table. All the subjects were extremely fatigued on surfacing. Three subjects developed substernal soreness on deep inspiration at the 60-foot depth while breathing oxygen and one who did not breathe oxygen also suffered from substernal soreness after three hours at 60 feet. Two subjects had numbness of the fingers throughout the period of oxygen breathing and one had mild nausea during the last thirty minutes of oxygen breathing. Four subjects developed joint pain after surfacing, two of whom required recompression for relief of the symptom (table IIl). It appeared that the table was faulty in the following respects: too rapid decompression from 165 to 60 feet, the danger of oxygen poisoning as a result of the two-hour period of oxygen breathing at 60 feet, prolonged breathing of dense air at 60 feet, and too rapid decompression from 60 feet to the surface.

The table was modified as follows:

Depth (feet of sea water)	165	140	120	100	80	60	50	40	30	20	10
Time at depth (minutes)	120	30	30	30	30	6 hr	6 hr	6 hr	12 hr	120	120

Six subjects were exposed to the pressures of this table without a previous wet dive. None developed joint pain, paresthesias, substernal soreness or nausea, but all were moderately fatigued after surfacing. Two subjects developed moderate frontal headache, one at the 20-foot depth and the other six hours after surfacing (table IIIm).

Tests of a decompression table for tenders.- The following table was tested:

Depth (feet of sea water)	165	140	120	100	80	60	50	40	30	To surface
Time at depth (minutes)	30	12	12	12	12	30	30	30	60*	5*

\*Breathing oxygen.

Ten subjects were exposed to the pressures of this table without a preceding wet dive. None of the subjects developed symptoms of caisson disease (table IIIn).

A procedure for the treatment of caisson disease and traumatic air embolism.- On the basis of present observations and previous experience the following treatment was devised:

Stops		Bends - pain only				Serious symptoms	
Rate of descent--25 ft per min	Rate of ascent--1 min between stops	Pain relieved at depths <u>less than</u> 66 ft. (29.4 lb.)		Pain relieved at depths <u>greater than</u> 66 ft. (29.4 lb.).		Serious symptoms include any one of the following: 1. Unconsciousness. 2. Convulsions. 3. Weakness or inability to use arms or legs. 4. Any visual disturbances. 5. Dizziness. 6. Severe shortness of breath or chokes.	
		Use table 1-A only when O <sub>2</sub> not available.		Use table 2-A only when O <sub>2</sub> is not available.  If pain does not improve within 30 min. at 165 ft. (73.4 lb.) the case is probably <u>not</u> bends. Decompress on table 2 or 2-A.		Symptoms <u>relieved</u> within 30 min. at 165 ft. (73.4 lb.)	Symptoms <u>not</u> relieved within 30 min. at 165 ft. (73.4 lb.).
Lb.	Ft.	Table 1	Table 1-A	Table 2	Table 2-A	Table 3	Table 4
73.4	165	--	--	30(Air)	30(Air)	30(Air)	30 to 120(Air)
62.3	140	--	--	12(Air)	12(Air)	12(Air)	30(Air)
53.4	120	--	--	12(Air)	12(Air)	12(Air)	30(Air)
44.5	100	30(Air)	30(Air)	12(Air)	12(Air)	12(Air)	30(Air)
35.6	80	12(Air)	12(Air)	12(Air)	12(Air)	12(Air)	30(Air)
26.7	60	30(O <sub>2</sub> )*	30(Air)	30(O <sub>2</sub> )*	30(Air)	30(O <sub>2</sub> )*or (Air)	6 hr.(Air)
22.3	50	30(O <sub>2</sub> )*	30(Air)	30(O <sub>2</sub> )*	30(Air)	30(O <sub>2</sub> )*or (Air)	6 hr.(Air)
17.8	40	30(O <sub>2</sub> )	30(Air)	30(O <sub>2</sub> )	30(Air)	30(O <sub>2</sub> ) or (Air)	6 hr.(Air)
13.4	30	↑ 5(O <sub>2</sub> ) ↓	60(Air)	60(O <sub>2</sub> )	120(Air)	12 hr.(Air)	1st 11 hr.(Air) Then 60(O <sub>2</sub> )or (Air)
8.9	20		60(Air)	↑ 5(O <sub>2</sub> ) ↓	120(Air)	120(Air)	1st 60(Air) Then 60(O <sub>2</sub> ) or(Air)
4.5	10		120(Air)		4 hr.(Air)	120(Air)	1st 60(Air) Then 60(O <sub>2</sub> ) or(Air)
Surface							

Time at all stops in minutes unless otherwise indicated.

If symptoms return while breathing air during treatment with any of the above tables, recompress to depth of relief but never less than a depth of 30 ft. and then complete decompression from this depth according to table 4.

\*If dizziness, nausea, muscular twitching or blurring of vision occurs while breathing oxygen, remove mask and proceed as follows: (a) if using table 1, complete remaining stops of table 1-A; (b) if using table 2, complete

remaining stops of table 2-A; (c) if using table 3, complete remaining stops of table 3 breathing air. At the discretion of the Medical Officer, oxygen breathing may be resumed at the 40 and 30-foot stops for a total of 90 minutes if using table 1 or 3 and 150 minutes if using table 2.

Recurrences.- Should symptoms recur following treatment with any of the above tables, recompress the diver to a depth giving relief. If relief occurs at depths less than 30 feet take diver to 30 feet and decompress from 30 foot stop to surface according to table 3. If relief occurs deeper than 30 feet, remain at the depth of relief for 30 minutes and then complete remaining stops of table 3 using air throughout.

The following general principles and additional details of the treatment of caisson disease and traumatic air embolism are included in the procedure of treatment:

1. Most frequent errors in treatment.
  - a. Failure to give treatment to doubtful cases.
  - b. Delayed recompression. The longer you wait, the deeper the diver will have to go for relief of symptoms.
  - c. Failure to treat the serious cases adequately according to table 3 or 4.
  - d. Failure to keep the "treated" diver near the chamber for a 24-hour period.
2. Symptoms of bends.
  - a. Symptoms may occasionally become temporarily worse if pressure is applied too rapidly. If this occurs, stop momentarily and then slowly raise the pressure at a rate tolerated by the diver.
  - b. In all cases, particularly serious cases with paralysis, always test the ability of the diver to stand up and walk the length of the chamber. Make this test routinely before leaving the depth of relief of symptoms, and also at the completion of the 30-foot stops.
  - c. Additional treatment includes first aid measures. Patient should be lying down during treatment to prevent, if possible, the movement of bubbles to the brain.
  - d. On completion of treatment, always keep the diver patient near the chamber for not less than 24 hours in order to treat any recurrences immediately.
3. Oxygen administration.
  - a. When oxygen is breathed, the fire hazard is always present. Do not smoke. Ventilate frequently to keep the chamber oxygen concentration low.

- b. The highest concentration of oxygen, preferably above 95 per cent, should be delivered to the diver patient. The mask used must be leak-proof in order to make the treatment tables effective.
  - c. If possible, humidify the oxygen to avoid dryness of the nose and throat.
- 4. Helium-oxygen mixtures.
  - a. At the maximum pressures of treatment, helium-oxygen mixtures (above 80:20 ratio) may be used to advantage instead of air in all types of treatment.
- 5. Tenders.
  - a. Tenders must always be present in the chamber with divers breathing oxygen.
  - b. Tenders require 60 minutes of oxygen during the last 60 minutes of the oxygen therapy period outlined in tables 1 and 2. If the diver is treated as outlined in tables 3 and 4, the tender will necessarily be subjected to the same treatment. Decompression for additional tenders who may subsequently enter the decompression chamber for short periods will be carried out in accordance with the standard diving tables.

#### DISCUSSION

Experience has shown that the majority of men with pain as the only symptom of caisson disease will be relieved at depths less than 66 feet. Adequate treatment can be achieved by compression to 100 feet combined with the use of oxygen at depths less than 60 feet during decompression. Limiting the maximal depth to 100 feet in these instances results in a considerable saving of time during decompression. As a result of the tests described in this report and past experience at the Experimental Diving Unit, tables 1 and 1A of the procedure are recommended for the treatment of patients with symptom of pain only relieved at depths less than 66 feet.

Occasionally a man with caisson disease having pain as his only symptom will not be relieved until depths greater than 66 feet are reached; however, some relief of pain will probably occur between 66 and 165 feet or, if not within this range of pressure, within thirty-minutes or less at 165 feet. Tables 2 and 2A of the treatment procedure provide a schedule of treatment for use under these circumstances. Tests described in this report indicate that these tables provide adequate treatment.

Symptoms suggesting involvement of the cardiorespiratory and central nervous systems are considered serious and are treated by prolonged recompression. For several years at the Experimental Diving Unit, all divers with

serious symptoms have been treated according to table 3 of the procedure of treatment. Rarely, a patient with serious symptoms cannot be adequately treated according to this table. Tests prescribed in this report indicate that treatment according to table 4 will be adequate under these circumstances. According to the treatment procedure, a patient with symptoms of traumatic air embolism would be treated in accordance with tables 3 or 4 because the symptoms of this condition fall in the serious category.

A guide for the treatment of recurrence of symptoms after initial treatment is included in the treatment procedure. However, if the procedure is correctly followed, such therapy will rarely be necessary.

O. E. VAN DER AUE  
Commander, (MC), USN

W. A. WHITE, JR.  
Lt. Commander, (MC), USN

R. HAYTER  
Lieutenant, (MC), USN

E. S. BRINTON  
Lieutenant, (MC), USN

R. J. KELLAR  
Lieutenant, (MC), USN

A. R. BEHNKE  
Captain, (MC), USN

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Table I.- Age and body specific gravity of subjects used in tests of tables for the treatment of caisson disease

Name	Age	Body specific gravity
Abe	22	1.075
Ati	24	1.085
Bun	27	1.054
Bur	28	1.071
Col	22	1.067
Coly	18	1.063
Coo	29	1.046
Cri	22	1.071
Cun	25	1.088
Den	27	1.085
Dre	30	1.080
Han	23	1.049
Hen	28	1.063
Hol	28	1.089
Joh	25	1.053
Kes	19	1.081
Kos	19	1.066
Kra	19	1.082
Man	25	1.078
Mar	22	1.087
Mey	24	1.063
Mur	22	1.080
Pac	25	1.099
Ple	29	1.102
Poo	19	1.092
Por	19	1.093
Ray	24	1.072
Ros	27	1.052
Sch	26	1.077
Sim	29	1.088
Ski	27	1.072
Whi	25	1.062
Wil	27	1.101

Table II.- Number of subjects with symptoms of caisson disease after a 130-foot dive and subsequent treatment for each table tested

Table tested	Time between exposure to 130-ft.dive and table (minutes)	No. of subjects exposed to table tested	No. of subjects with symptoms after 130-foot dive	No. of subjects with symptoms after treatment table
a 165-ft. air-O <sub>2</sub> (Bumed News Letter)	60	10 (Abe,Pac, Sim,Wil, Sch,Bun, Hen,Mey, Whi,Cun)	0	Requiring recompression 3 (Abe,Mey,Cun) Not requiring recompression - 3 - (Pac,Sim,Bun)
b 165-ft. air-O <sub>2</sub> (Bumed News Letter) plus 30 min. O <sub>2</sub> at 30 ft.	60	2 (Mar,Cri)	0	1 (Cri)
c 165-ft. air-O <sub>2</sub> (Bumed News Letter) plus 60 min. O <sub>2</sub> at 30 ft.	60	11 (Mey,Cun, Abe,Man, Kra,Kos, Kes,Coo, Poo,Dre, Mur)	3 (Kra,Kos Kes)	0
d 165-ft. air, 4 hr. at 30 ft.	60	2 (Mar,Dre)	0	0
e 165-ft. air, 4 hr. at 30 ft.	30	4 (Ati,Col, Ple,Joh)	0	0
f 165-ft. air, 4 hr. at 10 ft.	60	2 (Kes,Poo)	0	0
g 165-ft. air, 4 hr. at 10 ft.	30	4 (Ray,Wil, Mey,Whi)	0	0

Table II.- (Continued)

Table tested	Time between exposure to 130-ft. dive and table (minutes)	No. of subjects exposed to table tested	No. of subjects with symptoms after 130-foot dive	No. of subjects with symptoms after treatment table
h 100-ft. air-O <sub>2</sub>	30	12 (Abe, Sim, Wil, Sch, Pac, Bun, Hen, Col, Whi, Ati, Por, Ray)	0	0
i 100-ft. air-O <sub>2</sub>	60	12 (Abe, Sim, Wil, Sch, Pac, Bun, Hen, Mey, Cum, Col, Ati, Por)	0	0
j 100-ft. air	30	8 (Joh, Whi, Por, Af, Den, Coly, Sim, Hol)	0	0
k 100-ft. air	60	3 (Man, Kes, Ros)	0	0
l 165-ft. for serious cases, 2 hr. O <sub>2</sub> plus 22 hr. air at 60 ft.	No 130-ft. dive	6 (Hen, Col, Ple, Abe, Han, Poo*)	No 130-ft dive	Requiring re-compression- 2 (Ple, Abe) Not requiring recompression - 2 (Hen, Col)
m 165-ft. for serious cases, 6 hr. at 60 ft., 12 hr. at 30 ft. no O <sub>2</sub>	No 130-ft dive	6 (Sch, Pac, Bur, Ski, Mur, Kos)	No 130-ft dive	0
n 165-ft. air O <sub>2</sub> for tenders	No 130-ft dive	10 (Ati, Ray, Joh, Pac, Hen, Whi, Den. Bun, Wil, Ski)	No 130-ft dive	0

\*Did not breathe oxygen at 60 feet.

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