McCallum, R. I., Walder, D. N., Barnes, R., Catto, M. E., Davidson, J. K., Fryer, D. I., Golding, F. C. & Paton, W. D. M. (1966). Bone lesions in compressed air workers. *J. Bone Jt. Surg.* **48B**, 207–235.
Miles, S. (1966). *Underwater Medicine.* London: Staples Press.
Ohta, Y. (1966). Personal communication.
Paton, W. D. M. & Walder, D. N. (1954). *Compressed Air Illness.* Special Report Series 281. London: Medical Research Council.
Philp, R. B. & Gowdy, C. W. (1967). Blood lipid and cellular changes in rats after decompression sickness. *Proc. J. Int. Hyperbaric Physiol. Subaquat.* (in press).
Pol, B. & Watelle, T. J. J. (1854). Memoire sur les effects de la compression de l'air applique au creusement des puits a houille. *Ann. d'Hygiene Publique et de Medecine Legale.* Ser. 2, 241–279.
Rashbass, C. (1957). Aetiology of itching on decompression. Report. *Medical Research Council, R.N. Personnel Research Committee.* U.P.S. 167. London.
Rivera, J. C. (1964). Decompression sickness among divers: an analysis of 935 cases. *Milit. Med.* **129**, 314–334.
Rose, R. J. (1962). *Survey of Work in Compressed Air during the Construction of the Auckland Harbour Bridge.* Special Report No. 6. Medical Statistics Branch, Dept. of Health, Wellington, New Zealand.
Slark, A. G. (1962). Treatment of 137 cases of decompression sickness. Report. *Medical Research Council, R.N. Personnel Research Committee* 63/1030. London.
Stubbs, R. A. & Kidd, D. J. (1966). Computer analogues of decompression. In *Proceedings 3rd Underwater Physiology Symposium.* Ed. Lambertsen, C. J. Baltimore: Williams & Wilkins Co.
Triger, M. (1845). Influence de l'air comprime sur la sante. *Ann. Hyg. publ.* (Paris), **33**, 463.
Van der Aue, O. E., White, W. A., Hayter, R., Brinton, F. S., Kellar, R. J. & Behnke, A. R. (1945). *Physiologic factors underlying the prevention and treatment of decompression sickness.* Research Project Report X-443, No. 1. Washington: U.S. Navy Experimental Diving Unit.
Yarbrough, O. D. & Behnke, A. R. (1939). The treatment of compressed air illness utilizing oxygen. *J. Ind. Hyg. & Toxicol.* **21**, 213–218.

# 21

# *Saturation Diving: The Conshelf Experiments*

J. CHOUTEAU

In the conquest and the exploration of the sea, saturation diving is the most recent technique. It permits exploitation of the continental shelf which is impossible with the short excursions allowed by conventional diving.

The limits in depth and duration are imposed chiefly by the narcotic properties of gas mixtures inspired at pressure and by decompression sickness when returning to the surface (Fig. 21.1). Within limits it is possible to prevent the narcosis barrier by breathing mixtures lighter than air, such as helium or hydrogen. There remain, however, the decompression problems. The deeper the descent, the longer are the decompression stops required for a dive of the same duration. Further, the longer the duration at depth, the longer are the stops required up to a limit corresponding to the saturation of the dissolved gases in the body at the absolute pressure of the dive. This may be defined in the form of a ratio called 'the economic time of a dive' (Chouteau, Cousteau & Alinat 1966).

$$\text{The economic time of a dive} = \left[\frac{\text{Time at depth}}{\text{Time at depth} + \text{decompression time}}\right]$$

For increasing durations at any depth this ratio will at first diminish. It will reach a minimum near the time corresponding to saturation (i.e. 6 to 10 hours). Since the length of decompression then remains constant, for very long sojourns, the ratio will increase and tend to return towards unity.

It was the preliminary work on animals by Workman, Bond and Mazzone (1962) and by Barthelemy (1963) which defined the physiological conditions and gas mixtures required for extreme duration diving. In summary this work showed two conditions must be satisfied:

1. The inspired oxygen partial pressure should not exceed 309 mm Hg (0·41 ATS).

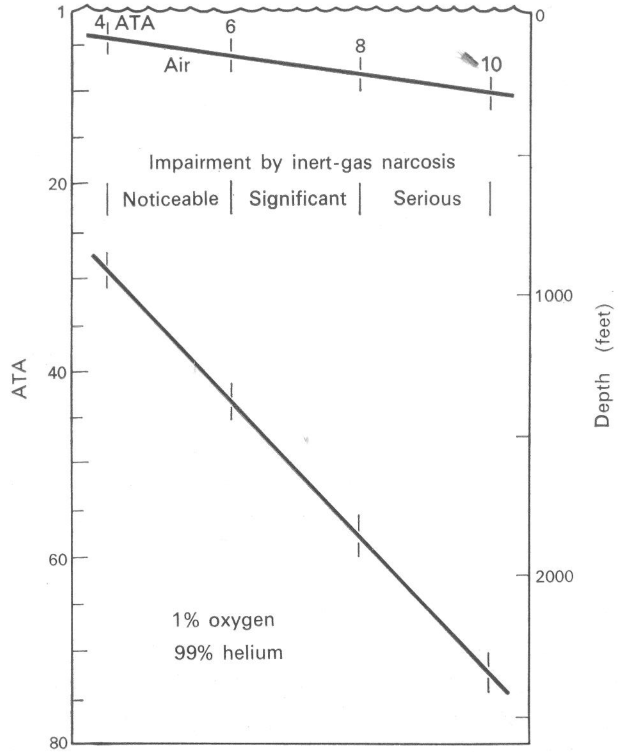


FIG. 21.1. Degrees of impairment by inert gas narcosis
The impairment experienced in diving with air is extrapolated for a 1% oxygen, 99% helium mixture on the assumption that helium is one ninth as narcotic as nitrogen (after Lanphier 1967).

2. The specific gravity (absolute density) should not exceed more than two or three times that of air at atmospheric pressure (i.e. 2·6 to 3·9 g/L).

These conditions were in fact achieved by the use of suitable oxygen–helium mixtures.

In this chapter we shall deal specifically with the long duration experiments performed by the French Office of Underwater Research (O.F.R.S.) which were started due to the stimulus of Cousteau and Alinat in a friendly relationship with the U.S. Navy programme. A general summary of our work is shown in Table 21.1, which gives the experimental conditions of Conshelf I, II and III, together with the previous animal and human experiments in pressure chambers.

## CONSHELF I

This first human experiment, made at the same time as that of Sténuit (see next chapter), took place near Marseille in September 1962. The under-



TABLE 21.1
The value for $P_{He}$ is the difference of absolute pressure and the sum of the other partial pressures

| *Code name* | *Subjects* | *Depth or pressure ft* | *ATA* | *Duration days* | $P_{O_2}$ *mm Hg* | $P_{N_2}$ *mm Hg* | $P_{CO_2}$ *mm Hg* | *Absolute density* g/L* STPD |
|---|---|---|---|---|---|---|---|---|
| Conshelf I | 2 men | 35 | 2·06 | 7·0 | 316 | 1192 | 0·4 | 2·650 |
| Conshelf II | 6 men | 31 | 1·95 | 30·0 | 302 | 1133 | 0·4 | 2·520 |
| | 2 men | 87 | 3·64 | 6·0 | 270 | 1030 | — | 2·560 |
| 'Merinos' | 2 sheep | 640 | 20·35 | 15·0 | 217 ± 29 | 124 | 65 ± 15 | 4·326 |
| 'Cachemire' | 2 goats | 640 | 20·35 | 14·0 | 169 ± 15 | 124 | 23 ± 7 | 4·326 |
| 'Alibouc' | 2 goats | 383 | 12·61 | 2·0 | 478 | 287 | 6 | 3·549 |
| 'Choutaqua' | 2 men | 383 | 12·61 | 5·0 | 177 ± 15 | 29 | 10·0 | 2·052 |
| Conshelf III | 6 men | 80 | 3·41 | 4·0 | 174 | 515 | 4·0 | 1·701 |
| | 6 men | 328 | 10·95 | 29·5 | 178 ± 24 | 64 | 4·0 | 2·146 |

* Calculated with respect to only $O_2$, $N_2$ and He. For dry air this value is 1·2923 (absolute density).

water house *Diogène* was a horizontal cylinder within a volume of 885 cu ft (25 m$^3$). It was positively buoyant and anchored on the sea-bed by 30 tons of ballast. An opening underneath permitted equilibration of internal pressure with the sea at 35 ft (2·06 ATA) and was used for an entrance by the divers or oceanauts. The air was supplied by compressors on an island about 600 m away using an open circuit at a ventilation rate of 14 to 17·5 cu ft/min. Electric power, telephone and television communications were provided with the surface ships *Calypso* and *Espadon*.

Two professional divers lived in this underwater house for 7 days breathing compressed air with a $P_{O_2}$ of 316 mm Hg (0·42 ATS). They made excursions into the sea for 4 or 5 hours a day at depths between 16 and 82 ft (1·5 and 3·5 ATA). The water temperature was 21°C but fell to 16°C on the third day. Their food was brought down to them in waterproof containers.

Clinical and physiological examination was made by Fructus and Chouteau, who spent 4 hours with the oceanauts each day. The results have been reported in detail previously (Fructus & Chouteau 1963; Cousteau, Fructus & Chouteau 1963). Their particular value is in the remarkable similarity in the behaviour of the two subjects, especially as regards their biological reactions. Chronologically three phases were distinguished.

*Phase one*. This began with an adaptation crisis characterized by:

1. Anxiety, which was well controlled in diver F except during sleep, and over compensated in W which aggravated its effects.
2. A moderate asthenia, possibly of a euphoric nature.
3. A number of metabolic and hormonal reactions, most of which may have been related to an 'alarm' syndrome, hypoglycaemia, lowering of adrenal hormones, a loss of erythrocyte potassium and excessive elimination of sodium.

These effects were, however, transient and did not appear to be the result of the action of the high partial pressure of oxygen or nitrogen. It is difficult to explain these reactions other than due to psychoneurogenic stress.

*Phase two.* From the second to the fourth day the divers became adapted. Life once again seemed possible and activity returned to normal. Then a gastrointestinal episode developed with a marked uropepsinuria—an indication of a second adaptation crisis.

*Phase three.* During the final 3 days all the evidence suggested that, detached from the surface, the oceanauts had now become fully adapted to their new surroundings. They viewed the possibility of a longer stay without worry and were only anxious about the prospect of the ascent.

Their azotaemia, at first normal, increased fairly regularly but never reached the high levels recorded in some cases of athletic effort. An almost constant rate of decrease of the red corpuscles and the granulocytes was also noted. On the seventh day W had lost nearly $1 \cdot 1 \times 10^6/mm^3$ red blood corpuscles and F nearly $0 \cdot 4 \times 10^6/mm^3$. The day after they returned to the surface both divers had already recovered $0 \cdot 2 \times 10^6/mm^3$. It is probable that this diminution was due to the slight hyperoxia ($Po_2 =$ 316 mm Hg), since it never occurred in other experiments when the $Po_2$ was less than 309 mm Hg.

At the end of their dive, although theoretically no decompression was necessary, they breathed intermittently an 80% oxygen, 20% nitrogen mixture for 3 hours before a symbolic decompression stop at 7 ft (1·2 ATA) on the way to the surface. Beyond the quick recovery of biological constants, the tests on the day after surfacing showed nothing but a slight change in the cortical EEG characterized by irregular activity with sporadic burst of alpha waves. The daily study of psychomotor reactions including the Wechler-Bellevue scale of understanding, the complex figure and number arrangements of Rey, the Benton visual retention test and a test of performance and reaction time, did not reveal any intellectual or psychic disorder. Small, sometimes inconsistent fluctuations of efficiency were, however, noted together with evidence of learning.

## CONSHELF II

Although this first experiment had demonstrated the feasibility of living at twice atmospheric pressure and working efficiently underwater for long periods, there were two special circumstances. First, the selected divers were highly trained and of above average constitution but the findings needed to be confirmed with others. Second, the limitation of the duration to 1 week was sufficient to demonstrate adaptation but insufficient to show if it would be maintained.



Thus, in July 1963, Conshelf II had three principal aims:

1. The corroboration and extrapolation of the *Diogène* results by exposing 5 normal subjects aged 31 to 43 with varied constitutions to 31 ft (1·95 ATA) breathing compressed air with an oxygen partial pressure of 302 mm Hg, ventilated at 70 cu ft/min (2000 L/min) for 30 days.
2. An extension of the depth by having two professional divers, aged about 40, live at 87 ft (3·64 ATA) for 6 of those days, their breathing mixture regenerated in a closed circuit. The mixture was to be composed of 50% air and 50% helium, i.e. 10·5% oxygen, 39·5% nitrogen and 50% helium with an absolute density, similar to that in the upper house, of about 2·56 g/L.
3. The demonstration of the logistic possibilities of establishing underwater houses far from a base and in a region of few resources.

A coral reef surrounding an accessible lagoon, *Shaab Rumi*, some 13 miles north-east of Port Sudan was the site chosen (Cousteau 1964). The operational aspects of the experiment did not, however, permit as complete a physiological study as in Conshelf I. Only careful clinical observation was possible.

The temperature of the sea was 28 to 30°C in the upper layers and the temperature in the upper house 30 to 32°C and 33 to 34°C in the lower. Humidity was close to 100%, especially in the lower house at 87 ft (3·64 ATA) where condensation was profuse and unending. The oceanauts dived for 3 to 5 hours each day from the upper house usually to 82 ft (3·5 ATA) but with excursions to 164 ft (6 ATA) and from the deeper house usually to 164 ft (6 ATA) but with excursions to 328 ft (10·95 ATA) in order to make biological observations and do photography and other underwater work.

Both groups of divers suffered from skin conditions such as prickly heat, pyodermatitis and furuncles and also diffuse external otitis of varying severity. These troubles proved the most severe in the group at 82 ft (3·5 ATA). The conditions were similar to lesions found in conventional divers but were apparently aggravated by the humidity and bacterial pollution of the habitats. Conversely flesh wounds healed more quickly; perhaps due to the raised $Po_2$.

It appeared that the adaptation crisis found in Conshelf I was negligible in these experiments. In the group living at 31 ft (1·95 ATA) some general emaciation, apathy and a discrete anaemia was, however, noticed.

The return to the surface at the end of their sojourn was preceded by breathing 80% oxygen, 20% nitrogen for three periods of half an hour, with half-hour intervals between, followed by two consecutive hours. Finally there was a 15-min decompression stop at 7 ft (1·2 ATA) before surfacing.

The return to the surface from the deeper house was preceded by breathing 50% oxygen, 50% nitrogen for 3 hours with decompression stops of 20 min at 49 ft (2·5 ATA) and 30 min at 39 ft (2·2 ATA) prior to a night in the house at 31 ft (1·9 ATA). There were no symptoms of decompression sickness. This experiment therefore confirmed the impressions from Conshelf I that it is possible for man to adapt to prolonged life under pressure and perform efficient work without developing any serious pathology.

## CONSHELF III

*Preliminary experiments*

Prior to the next stage of these experiments, Conshelf III at 328 ft (10·95 ATA), animal experiments were carried out at 640 ft (20·35 ATA) a pressure nearly twice as great. These experiments called 'Merinos', 'Cachemire' and 'Alibouc' were carried out in pressure chambers using an oxygen–helium atmosphere (Table 21.1). In sheep and goats there were no specific behaviour disturbances such as in sleep rhythm and rumination during a 15-day exposure. The blood chemistry also showed no undue changes (Chouteau, Bianco, Oriol, Coulboy, Aquadro, Alinat & Andrac 1967). These experiments also assisted in verifying the exponential decompression intended for Conshelf III.

A human experiment designated 'Choutaqua' (Aquadro & Chouteau 1967) followed in a pressure chamber at 383 ft (12·61 ATA). It permitted a thorough clinical study including EEG, ECG and the taking of samples of blood and urine during 3 days at pressure and 42 hours of decompression. No significant disturbances were found except for some 'rheumatism' and hormone fluctuations which may be explained by the discomfort of this unusual situation.

During the decompression, while passing from the oxygen–helium mixture to air at about 100 ft (4 ATA) both divers suffered from decompression sickness. These joint pains responded later to recompression.

*The decompression schedule*

For both the pressure chamber experiments and Conshelf III an exponential decompression was adopted using a modification of the Haldane theory suggested by Alinat. If $Po$ is the initial overpressure at instant $t$, the overpressure will be

$$P = Po\, e^{(-\log_e 2/T)\,.\,t} \qquad (1)$$

where $T$ is the half-time of tissue (Fig. 21.2). Thence

$$\frac{dP}{dt} = -P\frac{\log_e 2}{T} \qquad (2)$$



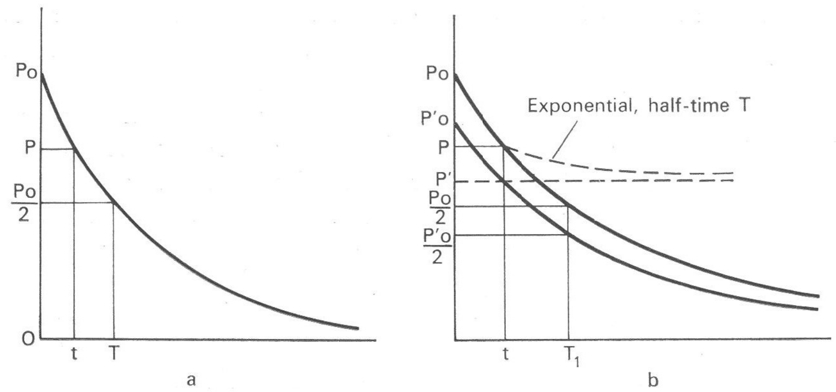


FIG. 21.2. Calculation of the decompression

Now suppose that instead of constantly referring to pressure $Po$ we allow it to vary in proportion to $P$. We shall call this pressure $P'$, which is in fact the ambient pressure to which the subject is exposed at instant $t$.

We then have $P' = P/n$, $n$ being a coefficient less than one. The overpressure is then

$$P - P' = P - \frac{P}{n} = P\frac{n-1}{n} \qquad (3)$$

Thence

$$\frac{dP}{dt} = -P\left(\frac{n-1}{n}\cdot\frac{\log_e 2}{T}\right) \qquad (4)$$

and

$$P = Po\, e^{\frac{-\log_e 2}{T}\cdot\frac{n-1}{n}\cdot t} \qquad (5)$$

its half-time

$$T' = \frac{n}{n-1}\cdot T \qquad (6)$$

The result is that if the ambient pressure $P'$ decreases from the value $P'o$, with a half-time $T'$, the overpressure in the tissues of half-time $T$, will decrease from the supposed initial value $Po$ according the same half-time $T'$ and the ratio of these two overpressures $P/P'$ which is the relative supersaturation will always be equal to

$$n = \frac{T'}{T' - T} \qquad (7)$$

For example, if we start with a saturation $Po = 11$ ATA with a tissue half-time of 2 hours (120 min) and if we allow the ambient pressure to decrease from 10 ATA according to a half-time $T' = 2^{h} \dfrac{1{\cdot}1}{1{\cdot}1 - 1} = 22^{h}$ the relative overpressure will remain 1·1 throughout the decompression.

It should be noted that the half-time $T$ and supersaturation ratio are not independent and a same value for $T'$ may be defined by an infinity of values for $T'$ and $n$ involved in equation (6), e.g.

$T' = 22^{h}$ may be obtained with $T = 2^{h}$ and $n = 1{\cdot}1$,
or $T = 1^{h}$ and $n = 1{\cdot}05$, or $T = 3^{h}$ and $n = 1{\cdot}16$.

Thus it is possible to use a continuous decompression in order that a tissue of determined half-time does not exceed a determined state of supersaturation.

In practice the continuous decompression technique has been used where the pressure in the pressure chamber is determined according to an exponential law relating to a 60-min tissue and a supersaturation between 1·06 ('Choutaqua' experiment: decompression from 383 ft (12·61 ATA) in 42 hours) and 1·18 (animal experiments: decompression from 640 ft (20·35 ATA) in 70 hours). For Conshelf III $n = 1{\cdot}03$ was adopted (decompression from 328 ft (10·95 ATA) in 84 hours) giving a very important safety margin.

## CONSHELF III, CAP FERRAT

During this experiment in 1965, six men aged 24 to 37 lived for 30 days in a spherical house 5·4 m in diameter at a depth of 328 ft (10·95 ATA). The $P_{O_2}$ was maintained, in an oxygen–helium atmosphere, at about 174 mm (0·23 ATS). The carbon dioxide was removed by soda lime and gas samples were analysed in the house by mass spectrometry and gas chromatography.

The oceanauts worked daily for about 4 hours around the house and made excursion dives to 426 ft (13·9 ATA) (Cousteau 1966). Their work included oceanographic investigations to disassemble, and reassemble an oil well 'Christmas tree'. The efficiency of their work was evaluated by comparison with previous studies at 82 ft (3·5 ATA). Medical and physiological observations, which had also been done over many months prior to the experiment, included a daily clinical questionnaire coded on IBM, general observations on behaviour, and psychological tests and bacteriological cultures. There was a strict control of the diet (Vaissière, Bourde, Aquadro & Chouteau 1966).

Analysis of the results has demonstrated the feasibility of man to live and work at such depths. Aquadro and Chouteau (1967) reported the



absence of any specific pathological lesions, decrement in performance or variation in the mental state of the subjects. However, there were minor problems including otitis externa, gastrointestinal disturbances, headaches and in one subject a slight febrile reaction.

In nearly all cases the pathological and psychological incidents observed may be related to neuro-endocrinological stress of psychic origin due to the restraints imposed by the restricted living and working conditions. Other factors are the unusual breathing mixture causing in particular either hypoxia or hyperoxia with hypercapnia and the accumulation of carbon monoxide (Umstead 1967) and other trace pollutants.

It is considered that only the problems of respiratory function and haemodynamics require further study before further even deeper experiments may be performed by man.

## THE LIMITS OF THE USE OF OXYGEN–HELIUM MIXTURES

Although the success of Conshelf, Sealab and Man-in-Sea programmes have permitted the practical solution of living under the sea, the ultimate depth at which this remains feasible has yet to be specified.

Experiments on animals in pressure chambers down to 640 ft (20·35 ATA) (Chouteau *et al.* 1967), on men at the same depth (Hamilton 1967), and at 720 ft (22·3 ATA) (Cabarrou *et al.* 1966) have revealed some interesting possibilities. Further, Chouteau, Cousteau, Alinat and Aquadro (1967a, b) have investigated the depth limits of a normoxic helium mixture. They studied four goats living for 10 days between 1280 and 1820 ft (39·71 and 56·17 ATA) under the conditions given in Table 21·2 and Figs. 21.3 and 21.4.

TABLE 21.2
The value for $P_{He}$ is approximately 220 mm Hg less than the absolute pressure

| *Simulated depth (ft)* | *ATA* | *Duration (days)* | $P_{O_2}$ *mm Hg* | $P_{N_2}$ *mm Hg* | $P_{CO_2}$ *mm Hg* | *Absolute density g/L* STPD | *Density relative to air g/L* | *Depth with equivalent density of air (ft)* |
|---|---|---|---|---|---|---|---|---|
| 1280 | 39·71 | 7 | 154 ± 29 | 22 ± 3·5 | 0·74 | 7·440 | 5·757 | 156 |
| 1820 | 56·17 | 3* | 191 ± 22 | 29 ± 3·5 | 0·74 | 10·741 | 8·312 | 240 |

* Includes some time spent at 1600 ft (48·5 ATA).

During the stay at 1280 ft (39·71 ATA) the animals showed no apparent alteration of general behaviour, sleep rhythm, feeding or rumination. At pressures greater than 1600 ft (49·39 ATA) an intermittent paresis of the hind limbs developed and the animals lay down. The few attempts at movement were slow, incoordinated and apparently difficult.

These manifestations disappeared completely and rapidly when the

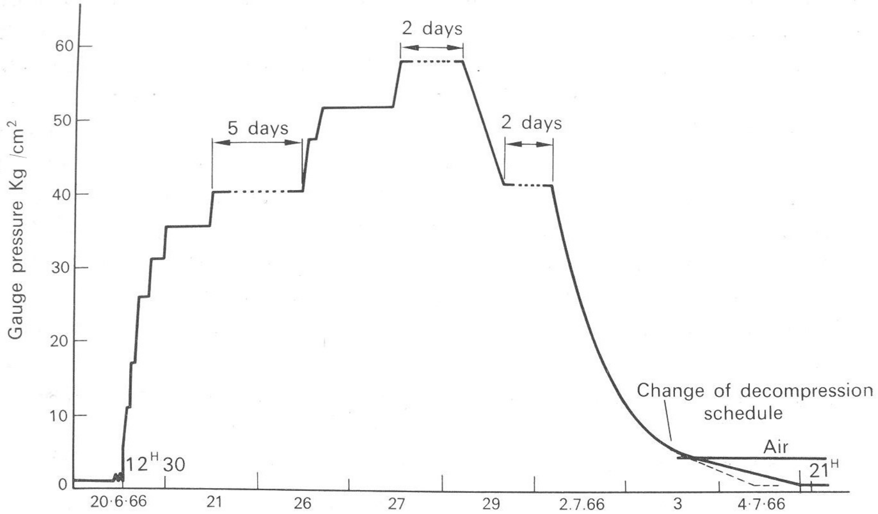


FIG. 21.3. The dive-profile of the oxygen–helium experiment with goats

1·033 Kg/cm² is equivalent to 1 Atmosphere and thus, for example, 40·4 Kg/cm² gauge is 40 Atmospheres absolute.

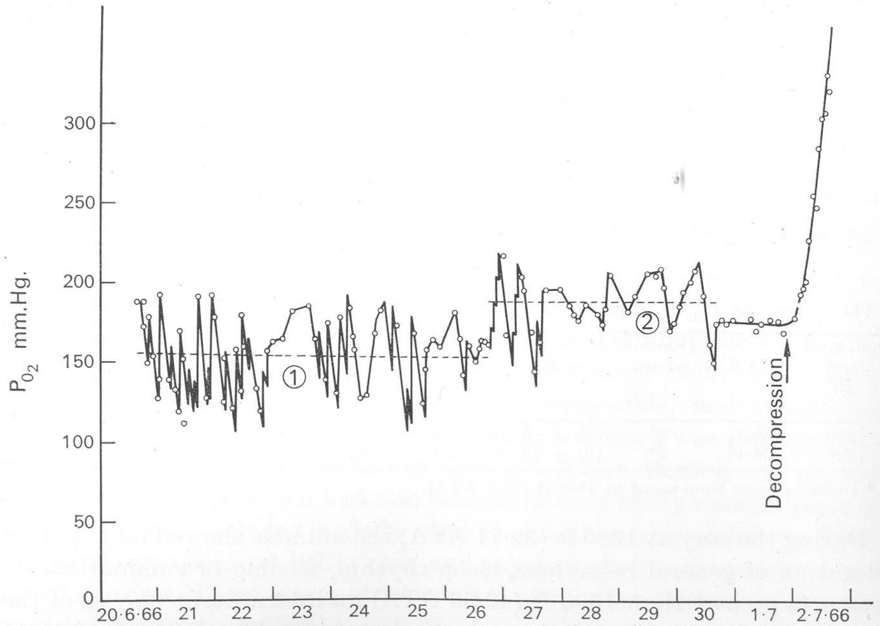


FIG. 21.4. Oxygen tensions during the oxygen–helium experiment with goats

(1) $Po_2$ mean value 154 mm Hg at 1280 ft (39·7 ATA).
(2) $Po_2$ mean value 191 mm Hg at 1820 ft (56·2 ATA).



$Po_2$ was raised to around 191 mm Hg (0·25 ATS). The animals stood up and resumed their normal activities. When this was repeated in a cyclic manner, the $Po_2$ fluctuating between 154 and 191 mm Hg (0·20 and 0·25 ATS), the same phenomena were again observed, alternating periods of lethargy and activity corresponding to the lower and higher oxygen pressures. During the remainder of the time at 1820 ft (56·2 ATA) the $Po_2$ was maintained at about 191 mm Hg (0·25 ATS) and the animals behaved as normally as in the exposures to 1280 and 640 ft (39·71 and 20·35 ATA). It, therefore, seems that a normoxic pressure is satisfactory to about 1300 ft (40 ATA) but beyond this pressure such an oxygen pressure causes hypoxia. A slight increase above normal will however bring a quick regression of the hypoxia.

In similar experiments with an oxygen–nitrogen mixture (Chouteau, Cousteau, Alinat & Aquadro 1967c, Chouteau, Cousteau & Alinat 1967), three goats were compressed to pressures of 163, 220 and 320 ft (5·95, 7·77 and 10·67 ATA) with a $Po_2$ of 154 mm Hg (0·20 ATS) (Fig. 21.5). In order to obtain, with the oxygen–nitrogen mixture, conditions similar to those with the oxygen–helium mixtures, it was necessary to have the identical specific mass, which would occur at 158 and 240 ft (5·7 and 8·3 ATA) equivalent to oxygen–helium at 1280 and 1820 ft (39·7 and 56·2 ATA), and kinematic viscosity, which would occur at 142 and 220 ft (5·3 and 7·6 ATA).

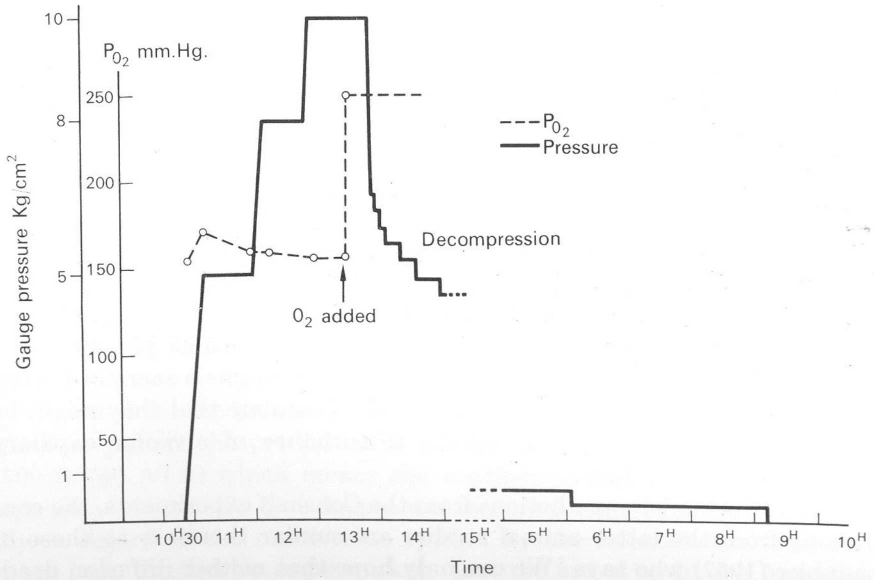


FIG. 21.5. The dive-profile and oxygen tensions of the oxygen–nitrogen experiment with goats

10 Kg/cm² is equivalent to 10·67 ATA.

At 159 and 220 ft (5·81 and 7·77 ATA) their behaviour was normal but at 320 ft (10·67 ATA) similar disturbances occurred as with the oxygen–helium experiments at 1600 and 1820 ft (49·39 and 56·17 ATA) characterized by paresis and the animals lying down. Raising the $Po_2$ in the chamber to 250 mm Hg (0·33 ATS) caused a return to normal activity within 5 min. It seems that this is the same phenomenon as in the two previous experiments. When the specific mass of a normoxic mixture exceeds a certain value there are hypoxic signs and symptoms. The hypoxia may be due to alveolar hypoventilation as a result of the specific mass of the inspired mixture or an increase in the coefficients of intrapulmonary diffusion (Fig. 21.6). If this is so it should occur with hypercapnia, the signs of which would not disappear with the late rise of $Po_2$. However, the animals never showed any hyperpnoea. Further a fall of $Po_2$ to around 110 mm Hg (0·14 ATS) in the oxygen–helium experiments at 1280 ft (39·71 ATA) did not cause any trouble and in the anoxia experiments, which were carried out to confirm the hypoxic nature of the signs and symptoms, it was necessary to use $Po_2$ levels as low as 75 mm Hg (0·10 ATS).

Alternatively the cause may be a cellular hypoxia of a histotoxic nature due to the increase of inert gas partial pressure. Such a mechanism has been described by Bennett (1966) as a possible explanation of the mechanism of narcosis at the synapse. However, the slight change of $Po_2$ associated with the reversibility of these phenomena cannot alter the $Po_2$ of the tissues by a significant amount.

The most likely mechanism is a disturbance of the alveolar-capillary exchange. There is either a decrease of the pulmonary diffusion of oxygen, an alveolar-capillary block altering the ventilation-perfusion ratio or both simultaneously. Finally the problem of an oxygen-diffusion dead-space cannot be excluded (Lanphier 1967).

Workman, Bond and Mazzone (1962) and Barthelemy (1963) have observed similar changes during their animal experiments at 193 ft (6·8 ATA). They described in animals sacrificed immediately after the experiments, pulmonary atelectasis and pneumonia which proved reversible since such changes were not present in the animals sacrificed later. Whatever the cause of these lesions we could postulate that they might be at least partially responsible for the disturbance of alveolar capillary exchanges discussed here.

After the optimistic predictions from the Conshelf experiments, the conclusions from the latter animal studies are similar therefore to those of Lanphier (1967) who says 'We can only hope that neither diffusion dead-space nor any unfamiliar problem will require elevation of oxygen pressure at great depth.' It seems that this hope is false and the oxygen will



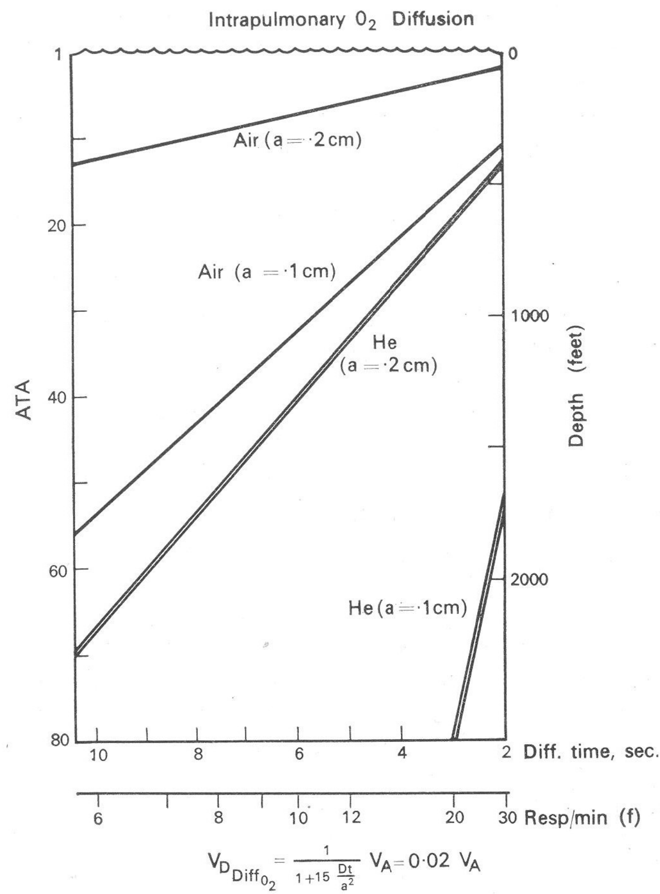


FIG. 21.6. Intrapulmonary diffusion of oxygen

The lines for air and helium indicate pressures beyond which the diffusion dead space for oxygen would exceed 2% of the alveolar volume at various respiratory frequencies. The resulting diffusion time is indicated. Diffusion distances (a) of 1 and 2 mm are represented, indicating the large influence of this factor (after Lanphier 1967).

have to be increased with the possibility of added complications as a result.

Nevertheless, the results of the animal experiments in oxygen–helium mixtures permit the prediction of successful saturation diving to about 1300 ft (40 ATA) which means the continental shelf is well within the capability of man. To dive deeper will require further experiments especially in regard to the restrictions applied by the tolerable limits of $Po_2$. It has been implied by some workers that the use of hydrogen instead of helium may permit further progress. However, recent work by Brauer and his colleagues, as discussed in Chapters 3, 7 and 8, is less hopeful. In a personal communication Brauer suggests that helium is 1/100th as narcotic as nitrogen whereas hydrogen is only 1/14th as narcotic. Further, hydrogen can in no way be regarded as inert in the sense applied to nitrogen, helium and neon as it has intrinsic biochemical functions.

REFERENCES

AQUADRO, C. F. & CHOUTEAU, J. (1967). Problems of extreme duration in open sea exposure. In *Proc. 3rd Underwater Physiology Symposium*. Ed. Lambertsen, C. J., pp. 98–108. Baltimore: Williams & Wilkins.
BARTHELEMY, L. (1963). Survie des animaux en pression. *Procès Verbal Etudes* GERS. N° 4/63, pp. 1.
BENNETT, P. B. (1966). *The Aetiology of Compressed Air Intoxication and Inert Gas Narcosis*, pp. 81–85. Oxford: Pergamon Press.
CABARROU, P., HARTMANN, H., WEINER, K. H., ALINAT, P. & FUST, H. D. (1966). Introduction à la Physiologie de 'Homo aquaticus'. *Presse Méd.* **74**, 2771–2773.
CHOUTEAU, J., COUSTEAU, J-Y. & ALINAT, J. (1966). Sur l'adaptation de l'homme à la vie sous marine en atmosphère comprimée naturelle et synthétique. *C. R. Acad. Sci., Paris*, **262**, 1962–1965.
CHOUTEAU, J., BIANCO, V., ORIOL, P., COULBOY, R., AQUADRO, C. F., ALINAT, J. & MME ANDRAC, C. (1967). Experimentation animale et humaine de vie prolongée sous pression en atmosphère oxygène–helium. Technologie et résultats biologiques. *Ann. Anesth.* Fr. **8**. N° spécial 1. pp. 238–280.
CHOUTEAU, J. COUSTEAU, J-Y., & ALINAT, J. (1967). Manifestations hypoxiques lors de la respiration sous pression de mélanges respiratoires ($O_2$–He, $O_2$–$N_2$) normoxiques. Influence de la masse spécifique de mélange. *J. Physiol. Paris*, **59**, 375.
CHOUTEAU, J., COUSTEAU, J-Y., ALINAT, J. & AQUADRO, C. F. (1967a). Experimentation animale de vie prolongée en oxygene–helium de 41 à 58 Bar. *J. Physiol. Paris*, **59**, 225.
CHOUTEAU, J., COUSTEAU, J-Y, ALINAT, J. & AQUADRO, C. F. (1967b). Sur les limites physiologiques d'utilisation de mélange oxygène–helium pour la plongée profonde et les séjours prolongés sous pression. *C.R. Acad. Sci., Paris*, **264**, 1731–1734.
CHOUTEAU, J., COUSTEAU, J-Y., ALINAT, J. & AQUADRO, C. J. (1967c). Sur les limites physiologiques de la plongée à saturation à l'air et aux mélanges synthétiques ($O_2$–He, $O_2$–$N_2$). Communication aux *Journées internationales d'Hyperbarie*. Marseilles. 28 Mai-3 Juin. (In press.)
COUSTEAU, J-Y. (1964). At home in the Sea. *Natl. Geographic. Washington D.C.* **125**, 465–507.
COUSTEAU, J-Y. (1966). Working for weeks on the sea floor. *Natl. Geographic Washington D.C.* **129**, 498–537.
COUSTEAU, J-Y., FRUCTUS, X. & CHOUTEAU, J. (1963). Operation Pre-continent N° 1. In *The Undersea Challenge*. Ed. Eaton, B., pp. 76–86. Great Britain: British Sub. Aqua. Club.
FRUCTUS, J. & CHOUTEAU, J. (1963). Aspects Physiologiques de la vie sous pression. *Med. Educ. Phys. Sport.* N° 1, 1–17.
HAMILTON, R. W. (1967). Physiological response at rest and in exercise during saturation at 20 atmospheres of He–$O_2$. In *Proc. 3rd Underwater Physiology Symposium*. Ed. Lambertsen, C. J., pp. 361–374. Baltimore: Williams & Wilkins.
LANPHIER, E. H. (1967). Interactions of factors limiting performance at high pressures. In *Proc. 3rd Underwater Physiology Symposium*. Ed. Lambertsen, C. J., pp. 375–384. Baltimore: Williams & Wilkins.
UMSTEAD, M. E. (1967). Carbon monoxide in the atmosphere of Sealab II. In *Project Sealab Report. An Experimental 45-day Undersea Saturation Dive at 205 feet*. Ed. Pauli, D. C. & Clapper, G. P., pp. 423–425. Washington D.C.: ONR Report ACR. 124.
VAISSIÈRE, R., BOURDE, J., AQUADRO, C. J. & CHOUTEAU, J. (1966). Problèmes diététiques poses par les maisons sous la mer. *Rev. Fr. Diétét.* N° 39, 1–7.
WORKMAN, R. D., BOND, G. F. & MAZZONE (1962). *Prolonged Exposure of Animals to Pressurized Normal and Synthetic Atmospheres*. Research Report N° 374. New London, Connecticut: U.S. Naval Submarine Medical Research Laboratory.

# 22

# *Saturation Diving: Man-in-Sea and Sealab*

J. B. MACINNIS & G. F. BOND

In the United States there is currently great industrial and military interest in the ability of men to work under the sea for long periods at great depths. In both the industrial and military pursuit of this goal, the common catalyst has been an immediate 'operational' requirement. The first human prolonged submergence diving experiments were carried out only as recently as 1962. Between 1962 and 1967 sixteen such studies were performed in the United States (Table 22.1). In addition, there have been recently several prolonged submergence dives for commercial objectives.

Unfortunately, the recovery of meaningful physiological and pathological data from most of these exposures was not as great as anticipated. One of the reasons for this was the speed at which the dives had to be conceived and completed. The second was that most of the dives were designed to demonstrate an 'operational' capability and, as a result, most physiological experiments were *ad hoc* and not effectively integrated into the over-all programme. Perhaps the most important reason was the problem inherent in recovering biomedical data from beneath the sea. During novel undersea operations such as Sealab or Man-in-Sea projects there is primarily an overriding concern for safety, and this is followed closely by a high number of operational requirements. It has been demonstrated that under these conditions an effective physiological data-gathering programme becomes exceptionally difficult to carry out. Not to be ignored in this context are the problems which arise from the hostility of the ocean environment towards delicate biomedical monitoring instruments. An additional problem lies in finding men who are both trained divers and experienced investigators and who are thus able to obtain significant *in-situ* data.

The significance of these factors should be kept in mind when considering

TABLE 22.1
Significant saturation dives made by United States investigators 1962–1967
(includes dry chamber experimentation and fresh- and salt-water submergence)

| *Date* | *Originator* | *Project name* | *Saturation depth (ft sea water)* | *Duration* | *Location* | *Dwelling type* | *Divers* | *Breathing gas* |
|---|---|---|---|---|---|---|---|---|
| *1962* | | | | | | | | |
| Sept. | E.A. Link | Man-in-Sea I | 200 | 24 hours | Villefranche, Mediterranean | Link cylinder, alum. 3 × 10 ft | Sténuit | 3% $O_2$ 97% He |
| *1963:* | | | | | | | | |
| April | Capt. G. F. Bond U.S. Navy | Genesis (D) | 150 | 6 days | Naval Medical Research Laboratory (NMRL), Bethesda, Md. | Dry chamber | Barth, Lavole, Fisher | $O_2$, He |
| Aug. | U.S. Navy | Genesis (E) | 200 | 12 days | NMRL, New London, Conn. | Dry chamber | Barth, Bull, Manning | 3·5% $O_2$ 6% $N_2$ 90·5% He |
| Dec. | U.S. Navy | Linear ascent from saturation in oxygen–helium | 300 | 24 hours | Experimental Diving Unit (EDU) Washington | Dry chamber | Kosimaki, Simeone | $O_2$, He |
| *1964:* | | | | | | | | |
| Feb. | U.S. Navy | Linear ascent from saturation in oxygen–helium | 300 | 24 hours | EDU Washington | Dry chamber | 2 divers | $O_2$, He |
| March | U.S. Navy | Linear ascent from saturation in oxygen–helium | 400 | 24 hours | EDU Washington | Dry chamber | Kennedy, Zuber | $O_2$, He |
| June | E. A. Link Univ. of Pennsylvania | Man-in-Sea II | 432 | 48 hours | Great Stirrup Cay, Bahamas | SPID (submersible portable inflatable dwelling) 8 × 4 ft rubber tent | Lindbergh, Sténuit | 4% $O_2$ 96% He |
| July | U.S. Navy | Sealab I | 193 | 11 days | Argus Island, Bermuda | *Sealab I* (40 × 9 ft cyl.) | Anderson, Barth, Manning, Thompson | 16% $N_2$ 4% $O_2$ 80% He |
| *1965:* | | | | | | | | |
| Feb. | Ocean Systems, Inc. | Man-in-Sea | 450 | 24 hours | Tonawanda, N.Y. | Dry chamber | Noble, Sténuit | 3% $O_2$ 97% He |
| Aug. | Ocean Systems, Inc. | Man-in-Sea | 650 | 48 hours | Tonawanda, N.Y. | Dry chamber | Christensen, Noble | 1·5% $O_2$ 98·5% He |
| Sept. | U.S. Navy | Sealab II | 205 | 45 days | La Jolla, Calif. | *Sealab II* (57 × 12 ft cyl.) | 28 USN, NASA, & civilian scientist divers | 4% $O_2$ 16% $N_2$ 80% He |
| Sept. | Westinghouse | Smith Mt Dam Project | 70–160 Excursions to 200 | 100 days | Smith Mt, Va. | Surface deck chamber | 12 teams of 4 divers | $O_2$, He |
| *1966:* | | | | | | | | |
| March | Westinghouse | Excursion study | 150 Excursions to 400 | 5 days | Baltimore, Md. | Surface chamber | Krasberg, Somers | $O_2$, He |
| May | Westinghouse | Gulf task | 70–160 Excursions to 240 | 150 days | Gulf of Mexico | Surface chamber | 18 teams of 6 divers | $O_2$, He |
| Nov. | Westinghouse | Narrangansett task | 100 Excursions to 165 | 11 days | Rhode Island | Surface chamber | 3 teams of 6 divers | $O_2$, He |
| *1967:* | | | | | | | | |
| April | Westinghouse | Excursion study | 330 Excursions to 620 | 4 days | Baltimore, Md. | Surface chamber | 3 divers | $O_2$, He |
| April | U.S. Navy | Sealab III | 450 | 12 dives of 2 days duration | EDU Washington | Dry chamber using wet pot | 12 four-man teams | $O_2$, He |
| June | Westinghouse | Project 600 | 350 Excursions to 600 | 4 days | Gulf of Mexico | Surface chamber | 7 divers | $O_2$, He |
| Aug. | Ocean Systems, Esso Production Research | Man-in-Sea III | 615 Excursions to 636 | 53·5 hours | Gulf of Mexico | Surface deck chamber | Patchette, Taylor | 1·5% $O_2$ 98·5% He |

the scope and relevance of the data gathered thus far from the Sealab and Man-in-Sea projects.

## THE UNITED STATES NAVY SEALAB PROJECT

*The concept*

The prime military objective of the United States Navy is the complete understanding and control of all those ocean areas under its domain. Inherent in this objective is the assurance that Navy divers have the maximum possible time-depth and performance ability to allow them to carry out multiple undersea military requirements which include submarine rescue, salvage and repair. In an attempt to extend this diving ability Bond and his co-workers initiated a series of experiments in 1957 to validate the concept of 'saturation' diving.

A 'saturation' dive is one in which the diver remains at a given ambient pressure long enough for his tissues to become essentially saturated with the inert gas he is breathing. It is generally thought that inert gas uptake into all body tissues proceeds at a compound exponential rate and that if a diver remains at a given depth for 24 hours or more he is considered to be 'saturated'. After this period his 'faster' tissues will not accept additional inert gas, although the 'slower' tissues may be accepting immeasurably small, but possibly significant amounts. It should be emphasized that the 24-hour saturation period is an arbitrary one, and may not fit information obtained from deeper or longer dives. For example, some advocates of the half-time tissue concept such as Kelly and Schreiner (1967) and Hamilton, MacInnis, Noble and Schreiner (1967) have indicated that a 320-min half-time tissue should be considered following 650 ft (20·7 ATA) for 48 hours.

The primary theoretical advantage of this novel technique is that once saturated, the diver can remain for an indefinitely long period without increasing his decompression obligation. Thus, the ratio of bottom time to decompression time can be markedly improved and diving efficiency increased. There are, however, two basic physiological problems associated with this concept. These are the selection of appropriate breathing mixtures and the development of safe decompression schedules for such prolonged exposures.

*Project Genesis*

In an attempt to ascertain the physiological hazards of prolonged residence in high-pressure environments, Workman, Bond and Mazzone (1962) exposed rats to air at 198 ft (7 ATA). At the end of 35 hours all animals were dead. Post-mortem examination demonstrated extensive pneumonitis, hyperaemia, haemorrhage and oedema of the lungs. These findings were attributed to the continuous exposure to the oxygen partial pressure of 1·4 ATS. A subsequent experiment with pure oxygen at 1·4 ATA led to reproducible mortality and pathological results. Further experiments with varying $Po_2$, time and depth suggested that an elevated $Po_2$ in any hyperbaric gas mixture can lead to serious pathological effects (Bond, unpublished).



Workman, Bond and Mazzone (1962) exposed rats and guinea pigs to 7 ATA for 14 days using a mixture of 97% nitrogen and 3% oxygen. Under these circumstances, the partial pressure of oxygen was equivalent to that at sea-level. During this exposure, the animals appeared lethargic. Following decompression, autopsied animals showed non-specific adrenal changes, pulmonary atelectasis and focal bronchopneumonia. Thirty days after the experiment, moderate histopathological lesions were found in the lungs of most animals. The authors attributed these lesions to the density of the respired atmosphere which was approximately seven times that of air at sea-level.

To validate this hypothesis, rats were exposed to 198 ft (7 ATA) for 14 days using a mixture of 97% helium and 3% oxygen. Immediately following decompression, and for up to 7 months subsequently, no significant histopathology was found. However, during the exposure there was a 46-g mean loss of weight. Further validation of the adequacy of this mixture was gained when monkeys were exposed to it for 12 days. However, one of the two animals sacrificed after decompression did demonstrate a slight hypertrophy of the zona fasiculata of the adrenal cortex. Although haematological and biochemical blood studies revealed no abnormalities in these and earlier animals, it should be noted that they were carried out after a 24-hour decompression period which possibly allowed time for return to normal. Studies also revealed no CNS or long bone tissue damage as a result of this exposure. The authors concluded from these experiments that helium–oxygen in the appropriate concentrations was a suitable synthetic atmosphere for mammals at high pressures.

In August 1962, Workman, Bond and Mazzone began using human volunteers. Synthetic environments of helium and oxygen were breathed for 6 days at sea-level and 99 ft (1 and 4 ATA) and for 12 days at 198 ft (7 ATA). This last human experiment was known as Genesis E.

*Genesis E.* For 12 days, 3 divers were exposed to a gas mixture at 198 ft (7 ATA) which was approximately 90% helium, 5·7% nitrogen and 3·8% oxygen. Blood and urine studies revealed no significant changes. The authors attributed a doubling of serum corticosteroids on the first day of the exposure to diver anxiety at depth. One subject showed a minor ECG change in the form of a slightly elevated S-T segment, but this change was considered to be clinically insignificant.

Altered ventilatory patterns due to the increased density of the breathing atmosphere were studied by Lord, Bond and Schaefer (1967). As might be expected, there was a decreased expiratory flow rate from breathing a gas with a density 1·5 times and a viscosity 1·13 times that of air.

The authors found that in the pressure range from sea-level to 99 ft (1·0 to 4·0 ATA) in air the greatest decrease in maximum expiratory flow (MEF) occurs at high lung volumes while from 99 to 198 ft (4·0 to 7·0 ATA) the greatest flow change occurs in low lung volumes. The long-term expiratory flow changes in hyperbaric helium were explained by the change in physical properties of the breathing mixture. A concurrent finding was that gases of high molecular weight and high ambient pressures of equal density produce similar changes in expiratory flow.

Psychophysiological tests performed by Weybrew, Greenwood and Parker (1964) revealed no significant autonomic nervous system changes. Although the partial pressure of oxygen was not significantly greater than that found in air at sea-level, the breath-holding time of all subjects was greatly increased. During Genesis E, exercise tolerance was studied by Lynch (1964). Following both the push-up and step-tests, no significant difference was found in pulse rates at sea-level or 198 ft (7 ATA). The authors concluded that no decrement in work performance resulted from the 12-day exposure. The method of linear ascent was used for decompression with satisfactory results.

### *Sealab I*

In July of 1964, Sealab I commenced in an undersea habitat at a depth of 193 ft water (6·8 ATA) near Bermuda (O'Neal, Bond, Lanphier & Odum 1965). For 9 days, four Navy volunteer divers lived and worked at this depth while breathing a mixture of approximately 79% helium, 17% nitrogen and 4% oxygen. The temperature inside the habitat was maintained at about 29°C (84°F) and the relative humidity at 72%.

In the course of the experiment some 30 physiological values were obtained daily from each subject (O'Neal *et al.* 1965; Bond 1966). These values included blood morphology and chemistry, basal metabolic function, body temperature and general physiological status. None of the values obtained during the dive indicated measurable changes in physiological well-being. This was also true when these values were compared with the 5-day pre-dive base line and the 5-day post-dive follow-up studies.

Two clinical observations of note were made during the exposure. There was an apparent slowing of all gross physiological and motor functions as well as an ability to acclimatize to the caloric loss in the gaseous and water environments. It was also noted that when oxygen levels were held at 4% or greater, the aquanauts reported an improved sense of well-being. This was attributed to the increased density of the breathing gas which was



about 1·6 times greater than sea-level air, causing an impaired pulmonary ventilation and a need for an increased molecular concentration of oxygen. Within the first 24 hours of exposure at 193 ft (6·8 ATA), after denitrogenation in the oxygen and helium atmosphere, exposure to compressed air resulted in an immediate and dangerous level of nitrogen narcosis, equivalent to that experienced breathing air at 350 ft (11·6 ATA). The authors concluded that once the body is essentially denitrogenated, susceptibility to nitrogen narcosis is significantly increased.

### *Sealab II*

In September of 1965 the United States Navy began its most ambitious prolonged submergence operation near La Jolla, California (Sealab II Project Group 1967). The habitat was placed in 205 ft sea water which ranged in temperature from 44 to 56°F. For 45 days 3 teams of 10 men occupied the habitat in turn, breathing a synthetic atmosphere of 188 to 268 mm Hg (3·5 to 5%) oxygen with less than 965 mm Hg (18·0%) nitrogen, and less than 22 mm Hg (0·4%) carbon dioxide, the balance (77 to 79%) being helium (Mazzone 1966). Temperature inside Sealab was maintained between 85 and 89°F, while relatively humidity remained about 76%. Of the 28 men who occupied Sealab, one man spent 30 consecutive days while another spent 15 days with both the first and third teams. The ages of the divers ranged from 25 to 50 years with a mean of 35.

During the exposure, slight and transient physiological changes were recorded (Hock, Bond & Mazzone 1967). Immediately following exposure to Sealab, oral temperature rose and continued to do so for the next 4 days. The highest temperature reached was a mean of 100·0 ± 0·08°F which was a 1·5°F increase from the mean base line value. Although a slow fall followed this peak, oral temperature remained about 1°F above pre-exposure values and was statistically highly significant. The authors postulate that this increase may be due to an increased thermal conductivity of helium.

The pulse rate increased from a mean of 71·4 ± 2·4/min to 84·9 ± 2·7 on the second day. Although a downward trend followed, pulse rates during the exposure remained higher than the base line values. Slight, but insignificant arrhythmias were found in some ECG tracings.

From a base line of 127 mm Hg, the systolic pressure rose slightly to a mean of 133 on the fifth day. Diastolic pressure rose from 80 to 86 mm Hg in the same period. These values remained relatively constant during the exposure with a slight downward trend in systolic pressure. It was considered that these changes in blood pressure were indicative of a slight cardiovascular response to stress.

There was a marked decrease in erythrocytes during the first 3 days when the value fell to 4·25 ± 0·13 $10^6/mm^3$ from a mean base line of

5·60 ± 0·22. These decreased levels were recorded until the ninth day after which a slow trend towards normal became evident. However, base line and exposure subjects were not always the same and these marked changes were not valid statistically. The one subject who spent 30 consecutive days in Sealab showed no further rise towards normal values. Hock *et al.* (1967) postulate that the decreased RBC levels were probably due to the slightly increased $Po_2$ (24 to 30% sea-level equivalent), fluid balance shifts, sequestration of cells, or increased erythrolysis. The authors also felt that the increased $Po_2$ may have caused a slight but steady decrease in neutrophils and a concurrent increase in lymphocytes.

From a base line of 47·8/100 ml immediately prior to the dive, the haematocrit fell to 45·6 on the second day and rose to 50·0 on the thirteenth day. The post-dive value was 50·4. The decreased value may be explained by haemodilution. The discrepancy between the fall in RBC and the increase in haematocrit has been attributed by the authors to a possible procedural error in the RBC count.

Haemoglobin levels fell from a base line mean of 15·35 ± 9·15 gm/100 ml to a value of 13·0 ± 0·74 on the third day. It rose slightly during the remainder of the exposure and returned to higher than normal values immediately post-dive. It is felt that these changes may also be due to the slightly increased $Po_2$.

Serum glutamic oxaloacetic transaminase and lactic acid dehydrogenase showed a clear increase from base line values, although immediately post-dive normal values were evident. This increase in serum enzymes was considered a response to the multi-stress environment. Urine volume increased initially, probably as a result of the factors which initiate cold-water diuresis. The trend back to the base line reflected poor collection techniques. Urine sodium, potassium and calcium increased slightly, probably as a result of general stress, exercise or dehydration.

Artificial exercise studies revealed no correlation between performance decrement and exposure time. However, the divers reported feelings of fatigue and lassitude, and after the dive maximal work capacity decreased.

Following dives into cold water a marked reduction in the temperature of the extremities and a slight rise in central core temperature was recorded. Upon return to the elevated temperature of Sealab and particularly following a hot shower, rectal temperatures fell sharply. This fall was due to peripheral vasodilation and partially explained the 'paradoxical shivering' observed by several divers. This phenomenon was a subjective feeling of being warm coupled with an objective and pronounced shivering. During the last phases of the dive, many divers noticed an increased tolerance to cold water. An increase in metabolic response to cold stress with loss of body heat was also noticed.



There were no neurological alterations resulting from the exposure, although EEG studies revealed slight transient changes during the time at depth. Psychophysiological examinations also revealed no deleterious effects from the prolonged dive.

It should be emphasized that although there were many slight changes

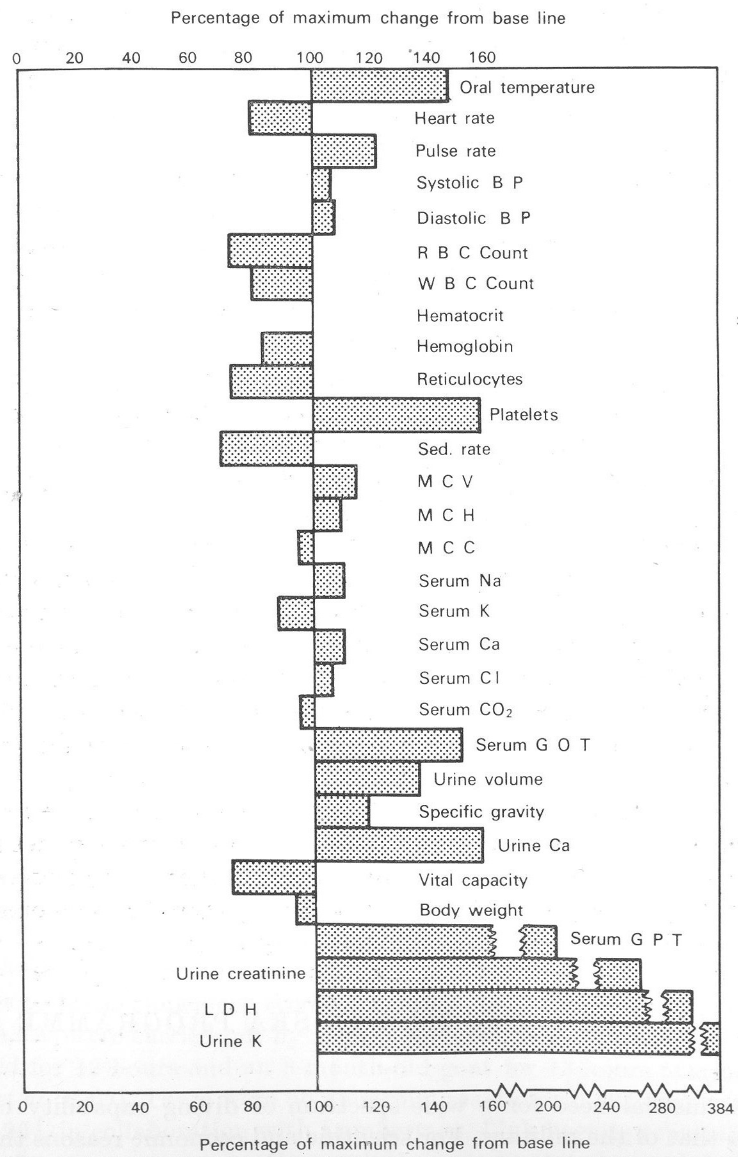


FIG. 22.1. Percentage of maximum deviation from pre-dive base lines of physiological parameters measured during Sealab II

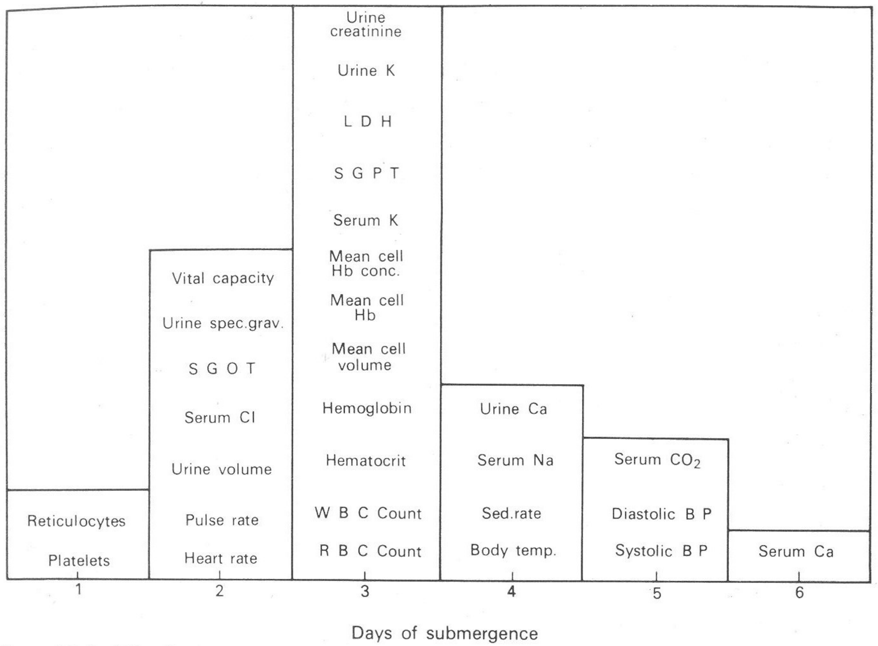


FIG. 22.2. The days on which occurred the maximum deviation of each physiological parameter during Sealab II (after Bond, Hock & Mazzone 1967)

in physiological function (Figs. 22.1 and 22.2) none of them was considered to indicate significant limitations to prolonged submergence at this depth under the given environmental conditions. Although the changes were only of a mild transitory nature, certain of them, such as body temperature, RBC count and serum enzymes indicate that further thorough studies are required to elucidate their etiology and pathophysiology.

Hock *et al.* (1967) concluded that in a Sealab type of exposure, general stress from multiple sources is the most consistent physiological deviant and that its impact is most severe during the first 5 days. They stated that this may indicate a need to condition the aquanaut prior to an operation in order to ensure peak performance during the critical period.

## OCEAN SYSTEMS MAN-IN-SEA PROGRAMME

### *The concept*

The industrial need for a wide spectrum of diving capability closely parallels that of the military. For scientific and economic reasons the free diver, able to live beneath the sea, has become a critical asset in the exploration and exploitation of the continental shelves. However, until recently,



comparatively little research has been carried out by American industry to ascertain the degree of physiological adaptation required for prolonged submergence. From 1962 until 1967 only one individual and one company were involved in laboratory experiments and open-sea trials to ascertain the feasibility and problems of the saturation concept.

During the 1950s Edwin A. Link was actively engaged in underwater archaeology. Although frequently carried out in shallow waters, such work is consistently time-consuming and Link became increasingly concerned with the inability of the working diver to remain for long periods beneath the sea. From his mechanical experience he designed a submersible decompression chamber (SDC) that would allow a resident diver maximum protection from the multiple undersea hazards (Ellis, Link & Marquet 1963). This diving system was the first of its kind to be used for prolonged submergence in the open sea.

### *Man-in-Sea Phase I*

Following the successful 200 ft (7 ATA) animal saturation exposures carried out by the U.S. Navy (Workman, Bond & Mazzone 1962) Link commenced his test programme in the Mediterranean. The first prolonged submergence, with Link himself as the test subject, was carried out on 28 August 1962. Eight hours were spent at 60 ft (2·7 ATA) breathing a mixture of 10% oxygen, 87 % helium and 3% nitrogen. Although he worked in the water for 90 min at this depth, no deleterious effects were observed during the exposure (Ellis *et al.* 1963).

In September 1962 Robert Sténuit became the first man to live in the sea at a depth of 200 ft (7 ATA). For 24 hours he worked in the water and rested in the SDC while breathing a mixture of approximately 3% oxygen, 94% helium and 3% nitrogen (Link 1963). Limited funds and personnel made it impossible to gather physiological data during this exposure. However, the subject was unaware of any difficulty during the dive except that of keeping warm while working in the sea. The original decompression schedule was prolonged to 67 hours due to minor decompression sickness in the right wrist. A thorough medical examination following the dive revealed no abnormality or changes from his pre-dive status.

### *Man-in-Sea Phase II*

Prior to further open-sea studies, a series of animal exposures at 400 ft (13·1 ATA) were carried out by Link in October of 1962. White mice were exposed for 12 hours and an 8-month-old goat for 13 hours at this depth (Ellis *et al.* 1963). There were no abnormal reactions in either species.

In 1964, in collaboration with Lambertsen, Link began preparations for the next open-sea exposure. Gas analysis equipment, to be used during the dive, was evaluated in a series of exposures in which mice were successfully saturated and decompressed from depths of 4000 ft (122 ATA) (MacInnis, Dickson & Lambertsen 1967).

In close collaboration with the United States Navy, Lambertsen and Link's life-support team participated in a series of saturation exposures at the Experimental Diving Unit in Washington, D.C. During late 1963 and early 1964 the U.S. Navy carried out two 24-hour exposures of 3 two-man teams at 300 ft (10 ATA), and one at 400 ft (13·1 ATA). Physical examination of all divers before and after these exposures revealed no abnormalities. In addition, Workman demonstrated once more the validity of his linear ascent decompression schedules following oxygen–helium saturation at these depths. The next step was open-sea confirmation of this information. In June 1964 Sténuit and Lindbergh lived and worked at 432 ft (14·1 ATA) for 49 hours (MacInnis 1966a). The water temperature at that depth was approximately 60 to 65°F. Although the two divers carried out repeated dives into the sea, the major problem during the exposure was their inability to maintain thermal equilibrium. A series of different mixtures of oxygen and nitrogen were inhaled in an attempt to mitigate the helium voice distortion. While breathing air at this depth, early and significant nitrogen narcosis was observed (Dickson & MacInnis 1967). During and following the 92-hour decompression, the divers were repeatedly examined by a physician. There was no evidence of clinical abnormalities resulting from the exposure. However, signs and symptoms of mild decompression sickness in Sténuit were observed 25 ft (1·76 ATA) from the surface but were rapidly resolved with return to increased ambient pressure and increased partial pressures of oxygen.

Electrocardiograms, chest X-rays, long bone X-ray surveys, blood and urine studies, history and physical examinations on both subjects on a yearly basis since the exposure have revealed no chronic deleterious effects when compared to the pre-dive base line values.

Further confirmation of the innocuousness of this prolonged exposure to great depths was obtained in February of 1965. Ocean Systems Inc. (a company formed by Link in conjunction with Union Carbide Corporation and General Precision, Inc.) carried out an experimental dive at 450 ft (14·6 ATA) in a dry laboratory chamber. Two divers, including Sténuit, were exposed to 3% oxygen, 96% helium and 1% nitrogen for 24 hours. Physical examination, EEG, ECG, blood and urine studies, long bone X-ray surveys and chest films were normal. Examination by specialists in neurology, ophthalmology and audiometry revealed no post-dive changes.

### *Exposure to 650 ft (20·6 ATA) for 48 hours*

To ascertain the adaptation of man to prolonged submergence at the deep edge of the continental shelf, two men in August 1965 lived in a small



chamber for 2 days at 650 ft (20·6 ATA). This experiment was designed to provide maximum physiological data prior to, during and after the dive (Hamilton, MacInnis, Noble & Schreiner 1966).

*Medical aspects.* Prior to the exposure, examinations for base line purposes were carried out: general medical history and physical status, haematology, serum chemistry, urinalysis, X-rays: chest films and long bone survey, EEG, ECG, pulmonary function, neurology, audiology, ophthalmology and ear, nose and throat. During decompression, physical examinations were also carried out by a physician at 328, 175 and 16 ft (10·9, 6·3 and 1·48 ATA). After decompression, two physicians again examined the divers. As in the base line studies, all findings were normal except for an average weight loss of 5½ lb.

*Subjective impressions.* During the compression, both divers reported slight dizziness which appeared to correlate with a sluggishness in equilibrating the middle ear space. During compression to 650 ft at a rate of about 10 ft/min, both subjects noted a fine hand tremor and discomfort during articulation of the large joints. Both findings were also reported by Royal Navy workers in a previous series of short-duration dives to depths between 300 and 800 ft (10 and 25·2 ATA) (Bennett 1967). In these short-duration dives, where the rate of compression approached 100 ft (3 ATS)/min, the symptoms were more severe but not debilitating. However, it is not possible at this stage to explain their etiology or define the role they may play in limiting future diving operations at greater depths, but recent work by Krasberg (1967) indicates that a slow rate of descent plus a low oxygen tension help to ameliorate the tremor and arthralgia.

While resident in the chamber, both divers requested the chamber temperature be elevated and maintained between 86 and 88°F. It was also noted that the thermal comfort range was narrowed from the normal air range of 13°F (72 to 85°F) to 2°F (86 to 88°F). It is interesting to note that the comfort range gradually decreased as the chamber pressure was reduced during decompression. The high thermal conductivity of helium *per se* combined with the further increase in thermal conductance, due to the compressed gaseous environment, probably accounted for this phenomenon. Heightened awareness of ambient temperature changes have also been noted by divers after prolonged water immersion (MacInnis 1966a). Its occurrence in a helium environment can probably be attributed to the adaptive response of the thermoregulatory centre, which at increased rates of caloric loss is probably more delicately triggered. It was felt that this altered stable state may also explain the confusion regarding cortical interpretation of heat and cold, since at times, both men had difficulty in discerning accurately if they were hot or cold.

Associated with the thermal regulation problem was a continual discomfort due to the high relative humidities associated with the experiment. Lowering of the relative humidity level to between 60 and 70% gave significant subjective relief.

Following the exposure, both divers admitted to undue fatigue. The important influencing stress factors in this particular exposure were: the confinement, changes in living habit, prolonged low-level anxiety, altered sleep patterns, lack of full-body exercise and increased density of the breathing gas. It is not possible at this time to ascertain how much of the fatigue might be attributed to the additional pharmacological effects of helium and the metabolic alterations arising from residence in such a synthetic environment.

*Cardiovascular system.* Heart rate information, acquired at standardized times, revealed an appreciable drop in resting heart rate during the period of maximum exposure. Following the 2 days at 650 ft (20·7 ATA) during decompression, the resting heart rates appeared to increase gradually. The etiology of the bradycardia is not clear but it may be that the high-pressure helium atmosphere exerts a pharmacological effect, since all the other multiple stressors would tend to cause tachycardia. No significant changes were observed in ECG patterns or blood pressure readings.

Pulmonary function studies carried out during the dive revealed the expected decrease in forced expiratory volumes at 1- and 2-sec intervals from the start. Maximum voluntary ventilation (MVV) followed a course reflecting the difficulty of breathing the dense gas and the results correlated well with density. More specifically, MVV showed a mean decrease of 59% in an atmosphere which was 3·8 times as dense as sea-level air. The maximal inspiratory and expiratory flow rates showed a decrease which paralleled the MVV. However, spirometer studies failed to reveal deficiencies in pulmonary function that were not due to the immediate effects of increased breathing-gas density.

Haematological investigations also revealed no serious disturbances as a result of the 2-day exposure to 650 ft (20·7 ATA). No abnormal morphology of the formed elements was noted. However, both divers had slightly elevated haematocrits at the beginning and throughout the dive. Parallel shifts in haemoglobin and red cell count suggested dehydration as a likely cause.

Blood chemistry values were essentially normal, but serum lactic dehydrogenase was slightly elevated for one diver and appreciably elevated for the other. It was concluded, however, that with the possible exception of serum enzymes it is doubtful if the haematological or biochemical parameters measured were useful indicators of the metabolic derangement associated with such exposures.

Urinalysis of both subjects was essentially normal but there was an



increase in urine output, probably as a result of the high humidity in the chamber combined with the cold-diuresis effect of residence in helium. In order to obtain a quantitative estimate of the physiological stress of the dive, urinary excretion of adrenal cortical stress hormones was measured: 'total' 17-hydroxy-corticosteroids increased in both divers, but of all the measured values, only one slightly exceeded normal. It was concluded that the stress-hormone analysis supports the subjective impression that a 48-hour exposure to 20 Atmospheres of helium is a relatively benign experience.

*Physiological performance experiments.* In an effort to demonstrate the ability of man to do useful work at extreme depths, experiments were devised in conjunction with Lambertsen to assess the response of a diver to exercise and breathing increased levels of carbon dioxide at 650 ft (20·7 ATA). The predominant factor affecting performance was the 3·8 increase in density in the breathing medium over that respired at sea-level. Other less influencing factors were: the possible pharmacological and pronounced thermal properties of helium, the high humidity, slightly increased oxygen tension and confinement with inactivity. An increased oxygen consumption of about 16 ml additional oxygen/min was observed for each litre/min of ventilation. A consistent increase in alveolar carbon dioxide was also noted when moderate exercise was carried out at maximum depth. When compared with sea-level, the results were statistically significant. It should be noted that, despite the resting bradycardia, the heart rate responded to exercise in essentially normal fashion under these pressure conditions (Fig. 22.3).

When ventilatory response to carbon dioxide was measured at high pressure, there was evidence of an increase or shift to the right of the controls, but there was little change in the slope of the curves (Fig. 22.4). The authors were uncertain as to the origin of this shift but suggested long-standing accumulation of carbon dioxide, extra breathing resistance and inert gas narcosis as possible causes.

*Psychological measurements.* During the exposure, repeated attempts at evaluation of psychomotor and higher cortical functions were attempted and results revealed no serious decrement to learning or routine calculating ability. However, subtle changes were evident that required further investigation. Despite the experimental limitations of a pursuit rotor experiment, there was no important motor performance decrement resulting from the exposure.

*Neon breathing.* Two divers were permitted to breathe a 90% neon, 10% oxygen mixture for 30 min at 650 ft (20·7 ATA) (Schreiner *et al.* 1966). With a density equal to air at 500 ft (16·2 ATA), the neon mixture was, at 650 ft (20·7 ATA), one of the most dense gas mixtures ever breathed by

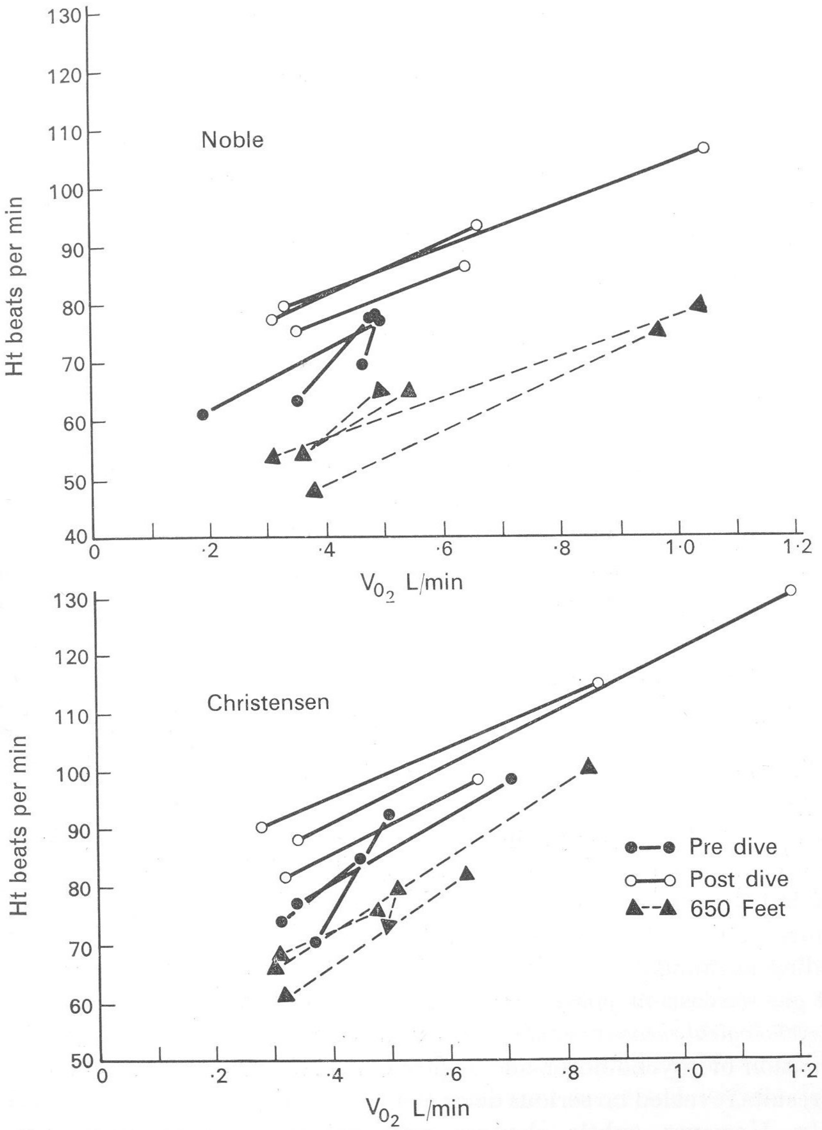


FIG. 22.3. Cardiac rate response to exercise (after Hamilton, MacInnis, Noble & Schreiner 1966)

man for more than a few minutes. Both divers were aware of the increased respiratory resistance although they stated that it was not difficult to breathe at rest. Pursuit rotor, other psychological tests and simple observation revealed no measurable performance changes as a result of breathing this neon mixture at 650 ft. It was therefore concluded that the narcotic



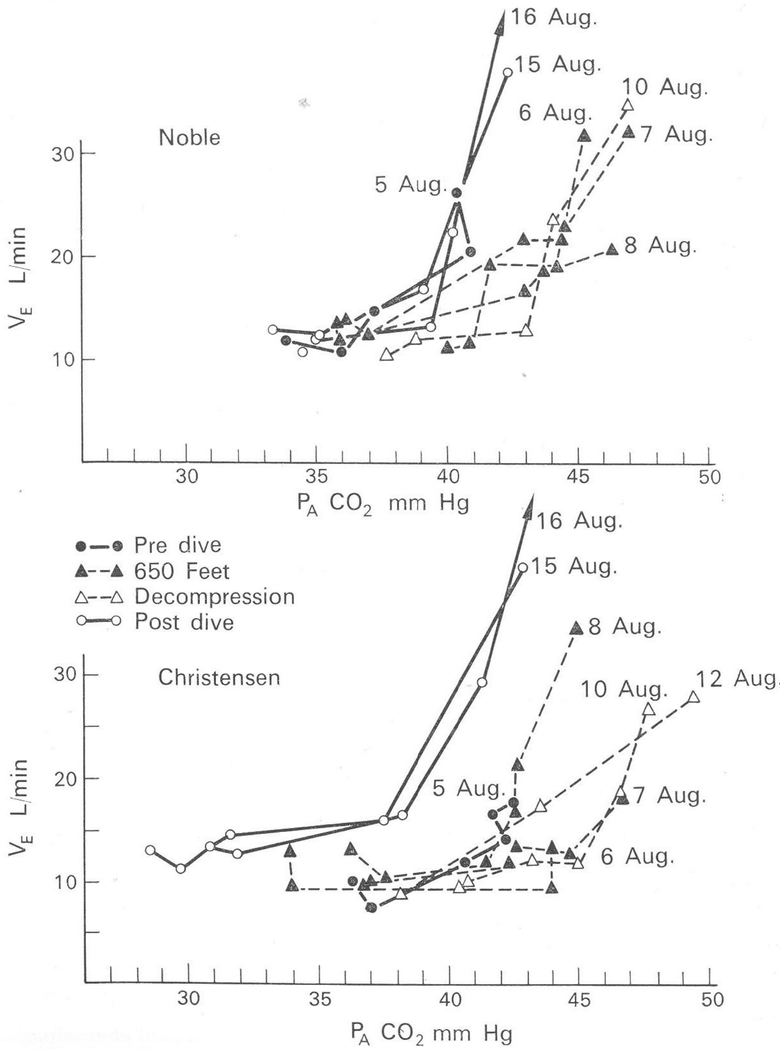


FIG. 22.4. Carbon dioxide response curves (after Hamilton, MacInnis, Noble & Schreiner 1966)

properties of neon at 16 atmospheres are probably no worse than those of helium.

In both the Sealab and Man-in-Sea programmes, the data obtained during the exposure of men and animals to increased pressures for prolonged periods, either alone or in groups, to date revealed no significant or limiting pathophysiology (MacInnis 1966b). Although there have been minor and transient changes in physiological functions as a result of these exposures, there is at present no evidence to suggest that man will not be permitted prolonged submergence at all depths of the continental shelf. In August 1967 two Ocean Systems divers made a 615 ft 53·5 hour saturation dive in the Gulf of Mexico. At depths of 625, 632 and 636 ft (21·2 ATA) almost 7 hours of useful work was carried out during an exhaustive work-performance study. No data from this joint technical programme with Esso Production Research is available at the time of writing. However, it can be said with authority that no significant performance decrement or physiological change was subjectively or objectively noted.

However, the sparse information gathered so far tells us little about possible chronic effects or the long-term results of repeated saturation exposures. Further, new techniques, such as continual excursion dives from a saturation level, may impose unique physiological stresses and will consequently demand careful and exhaustive study.

From the experience of the past 5 years there can be little doubt that as much data as possible, particularly that pertaining to safety, must be obtained methodically in the laboratory prior to prolonged submergence beneath the sea. However, it has also become evident that there is no substitute for rigorously selected physiological function and psychomotor performance studies conducted in the sea itself. The information to be sought must be obtained with as little inconvenience as possible to the diver. It must be gathered by investigators trained to work in the ocean environment. Only with a well-planned and thorough data retrieval approach will man be able to continue his advance into the sea with authority.

## REFERENCES


Bennett, P. B. (1967). Performance impairment in deep diving due to nitrogen, helium neon and oxygen. In *Proc. 3rd Underwater Physiology Symposium.* Ed. Lambertsen, C. J. Baltimore: Williams & Wilkins.

Bond, G. F. (1966). Effects of new and artificial environments of human physiology. *Arch. environ. Hlth.* **12**, 85–90.

Dickson, J. G. & MacInnis, J. B. (1967). Confluence of physiological environmental and engineering factors in prolonged diving at extreme depths. In *Proc. 3rd Underwater Physiology Symposium.* Ed. Lambertsen, C. J. Baltimore: Williams & Wilkins.

Ellis, J. P., Link, E. A. & Marquet, W. M. (1963). *Man in Sea Project.* Test Series Report No. 1 Link Division, General Precision Equipment Corp. (unpublished Technical Memorandum).

Hamilton, R. W., MacInnis, J. B., Noble, A. D. & Schreiner, H. R. (1966). *Saturation Diving at 650 feet.* Tonawanda, New York: Ocean Systems Inc.

Hock, R. J., Bond, G. F. & Mazzone, W. F. (1967). *Physiological Evaluation of Sealab II. Effects of Two Weeks Exposure to an Undersea 7-Atmosphere Helium–Oxygen Environment.* Deep Submergence Systems Project Publication. Anaheim, California: Nortronics Division, Northrop Corp.

Kelly, P. L. & Schreiner, H. R. (1967). Computation methods for decompression from deep dives. In *Proc. 3rd Underwater Physiology Symposium.* Ed. Lambertsen, C. J. Baltimore: Williams & Wilkins.

Krasberg, A. (1967). Saturation diving: vertical excursion techniques. In *The New Thrust Seaward.* Washington: Marine Technology Society.





Link, E. A. (1963). Our Man-In-Sea project. *Natl. Geographic,* **123**, 713–731.

Lord, G. P., Bond, G. F. & Schaefer, K. E. (1967). Breathing under high ambient pressure. *J. appl. Physiol.* **21**, 1833–1838.

Lynch, J. I. (1964). *Exercise Tolerance Studies in an Artificial Atmosphere under Increased Barometric Pressure.* Research Report 23, No. 20–1, 1–11, New London, Connecticut: U.S. Navy Medical Research Laboratory.

MacInnis, J. B. (1966a). Living under the sea. *Sci. Amer.* **214**, 24–33.

MacInnis, J. B. (1966b). The medical and human performance problems of living under the sea. *J. Canad. med. Assoc.* **95**, 191–200.

MacInnis, J. B., Dickson, J. G. & Lambertsen, C. J. (1967). Exposure of mice to helium–oxygen atmosphere at pressure to 122 atmospheres. *J. appl. Physiol.* **22**, 694–698.

Mazzone, W. F. (1966). Human physiology aspects of Sealab II. In *Man's Advance Into the Sea.* Washington: Marine Technology Society.

O'Neal, H. A., Bond, G. F., Lanphier, R. E. & Odum, T. (1965). *An Experimental 11-day Undersea Saturation Dive at 193 Feet.* Report ACR-108, 1–58. U.S. Office of Naval Research.

Pauli, D. C. & Clapper, G. P. Ed. (1967). *An Experimental 45-Day Undersea Saturation Dive at 205 Feet.* Sealab II Project Group. Washington: Office of Naval Research.

Schreiner, H. R., Hamilton, R. W., Noble, A. D., Trovato, L. A. & MacInnis, J. B. (1966). Effects of helium and neon breathing on man at 20 ATM pressure. *Fed. Proc.* **25**, 230.

Weybrew, B. B., Greenwood, M. & Parker, J. W. (1964). *Psychological and Psychophysiological effects of Confinement in a High-pressure Helium–oxygen–nitrogen Atmosphere for 248 hours.* Research Report 23, No. 23, 1–15. New London, Connecticut: U.S. Navy Medical Laboratory.

Workman, R. D., Bond, G. F. & Mazzone, W. F. (1962). *Prolonged Exposure of Animals to Pressurized Normal and Synthetic Atmospheres.* Research Report 26, No. 5, 1–19. New London, Connecticut: U.S. Navy Medical Research Laboratory.