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The Use of the Pneumatic Analogue Computer for Divers

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In 1962 a solution to the projected operational requirements for diving and submarine escape in the Royal Canadian Navy appeared to be the use of a breathing apparatus capable of maintaining the partial pressure of oxygen at a predetermined level independent of ambient pressure. It followed, therefore, that the diluent inert gas would be administered in a variable mixture dependent on depth.

Using a variable mixture breathing apparatus, the inert gas partial pressure/time profile for any given exposure will be different from the profile resulting from the same exposure using a constant-mixture breathing apparatus.

Since existing decompression tables are based on constant-mixture exposures, they would be inappropriate for variable-mixture exposures. It was necessary, therefore, to review the technique used to compute decompression schedules.

The classical work of Boycott, Damant and Haldane (1908), developed by Behnke (1942), Hempleman (1952) and Rashbass (1954) assumes that:

1. *The partial pressure of inert gas in the body tissues will change with the ambient pressure of the breathing gas in accordance with the laws of diffusion.*
2. *The inert gas partial pressure within the alveoli is in equilibrium with the inert gas partial pressure in the blood.*
3. *The results of successive pressure changes will be an algebraic sum.*
4. *A degree of inert gas supersaturation is tolerated by the body without symptoms.*

METHODS OF DECOMPRESSION COMPUTATION

The technique used to compute decompression schedules is based on the solution of a simplified version of the gas diffusion equation, namely,

$$\frac{\mathrm{d}P_{\mathrm{T_N}}}{\mathrm{d}t} = -K(P_{\mathrm{T_N}} - P_{\mathrm{A_N}}) \qquad (1)$$

which for the specific case of constant ambient inert gas partial pressure of the breathing mixture has the form

$$P_{\mathrm{T_N}} = P_{1_\mathrm{N}} + (P_{0_\mathrm{N}} - P_{1_\mathrm{N}})\,\mathrm{e}^{-0{\cdot}693t/T_{1/2}} \qquad (2)$$

where $P_{\mathrm{A_N}}$ = ambient inert gas partial pressure,
$P_{\mathrm{T_N}}$ = tissue inert gas partial pressure,
P_{0_N} = tissue initial inert gas partial pressure,
P_{1_N} = tissue final inert gas partial pressure = ambient inert gas partial pressure,
t = time in minutes,
$T_{1/2}$ = hypothetical tissue compartment half-time in minutes.

During an increase in ambient pressure, the inert gas partial pressure in each individual hypothetical tissue compartment is computed, assuming that the descent is linear. It is current computation practice to apply the total pressure gradient to each of the compartments for half the descent time or to apply half the pressure gradient to the compartments for the total descent time. These calculations are normally made using mathematical tables or a slide rule. Similarly for the total time at maximum pressure, the inert gas partial pressure in each compartment is calculated using the new pressure gradients and the total time at depth. These values are used as the initial conditions for the calculation of the decompression schedule.

For each compartment half-time a certain supersaturation ratio is assigned. One compartment will limit the initial phase of the ascent or decompression. A trial ascent is made to the ambient pressure suggested by this limiting compartment. The effect of this trial ascent on the inert gas partial pressures in the other compartments is calculated, assuming the ascent to be linear. Inspection may show that the time taken to ascend allowed the ratios for the controlling tissue compartment or one of the other compartments to be exceeded. This means that a reiterative process must be used to ensure that no ratio is exceeded during ascent. This procedure is repeated for each compartment in turn and successive stops determined until the surface may be reached without exceeding the ratios. The arbitrary choice of time at stops gives rise to considerable doubt regarding the entire procedure.

The reiterative sequence of approximate calculations is laborious and extremely slow. It was felt that the solution to the basic diffusion equation would be less tedious if carried out graphically. In addition, it was felt that a linear descent and ascent equation should be derived for more accurate computation during these phases of the dive. The graphical method has shown that decompression schedules can be obtained more quickly and in close agreement with experimental results. However, the major advantage was a clearer presentation of the interplay of the half-times and pressure ratios of the various compartments. In fact, it has been shown that the total time required for decompression from a given dive decreases as the number of stops increases and the time intervals at stops become shorter. This suggests that the minimum time for decompression from a given dive approaches a limit which is obtained by following a continuous ascent curve of a particular type (Bradner & MacKay 1963).

While this graphical method of analysis improved the calculation of decompression schedules it contained many limitations, since linear descents, precise times at constant depth and reiteration are still required to obtain the safe continuous ascent curves for a multi-compartment system. Therefore, a method of continuous computation was required which would be valid regardless of the descent or compression time schedule. In addition, the computation should provide direct indication of the ascent pattern for a minimum decompression time. The simplest method of achieving this computation appeared to require the use of analogue techniques (Groves & Munk 1963).

PNEUMATIC ANALOGUES

It was therefore decided that a simple analogue computer should be designed which would carry out the tissue compartment partial pressure calculations continuously, regardless of descent pattern and time at depth. The simplest physical analogue of the gas diffusion equation is a pneumatic resistor through which a gas can be introduced into a fixed volume. A resistor-volume combination can be adjusted to operate at a particular diffusion half-time constant. Four such resistor-volume combinations were assembled on a single manifold. If pressure is applied to the manifold to simulate a dive then the pressure measured in each of the fixed volumes could represent the partial pressure of gas in a hypothetical tissue compartment. In view of the long time required in the past for decompression computation, it was decided that the first pneumatic analogue computer (Mk I P) should be adjusted for operation in seconds rather than minutes.

The graphical method of solution of the four simultaneous diffusion equations was used to analyse the available decompression tables. The pneumatic analogue computer, when programmed in artificial time, was found to confirm these values. The supersaturation ratios determined from this analysis are shown in Table 16.1.

The larger the value of a supersaturation ratio for a given half-time, the greater the risk of incurring symptoms of decompression sickness, hence the largest values derived from the tables can be construed as describing a 'bends' threshold for man.

TABLE 16.1

Maximum supersaturation ratios (P_{T_N}/P_A)*

Source of tables	*Half-time in minutes*				*Range of tables*
	10	20	40	80	
Diving					
Nil decompression curve	2·7	2·2	1·8	1·6	7·06 ATA— 5 min ; 2·2 ATA—180 min
USN (1958)	2·6	2·1	1·85	1·65	10·1 ATA—180 ,, ; 5·3 ATA—720 ,,
RN (1956)	2·4	2·0	1·75	1·6	7·06 ATA— 15 ,, ; 2·8 ATA—120 ,,
French G.E.R.S. (1959)	2·3	2·3	2·0	1·6	8·6 ATA— 15 ,,
Caisson workers					
U.K. (1959) (4-hour shift)	1·9	1·95	1·8	1·5	4·4 ATA—240 min ; 2·4 ATA—240 min
New York (1958)	1·9	2·05	1·8	1·65	4·4 ATA— 30 ,, ; 2·2 ATA—240 ,,
New Zealand (1961)	1·9	1·9	1·7	1·5	4·4 ATA—240 ,, ; 2·4 ATA—240 ,,
Computer	2·65	2·15	1·85	1·65	

* Where P_A is the total ambient pressure.

The ratios selected for future computation are intermediate between the highest values found from the most valid data. Since the tables can be described in terms of four half-times and four ratios, it was decided to construct an analogue computer in real time to reproduce the tables when exposed to the appropriate pressure time profile. Half-times of 10, 20, 40 and 80 min with inert gas supersaturation ratios of 2·65, 2·15, 1·85 and 1·65 respectively were used. When constant gas mixtures are used in diving, it is appropriate and more convenient for the pneumatic computer to compute theoretical inert gas pressures using total gas pressure. Thus for compressed air diving, the supersaturation ratios are increased by the reciprocal of the inert gas mole fraction.

In this analogue computer (Mk II P) the pressure in each of the four parallel compartments is sensed by a Bourdon tube. The deflection of each Bourdon tube is divided by the ratio appropriate to that compartment. The resulting deflections are compared. The largest deflection is an indication of the minimum pressure (depth of water or altitude) to which it is safe to ascend. This indication is presented on the same scale as ambient pressure. When tested in the laboratory and in a hyperbaric chamber and subjected to typical dive profiles specified by the tables (*U.S.N. Diving Manual* 1958), the computer ascent depth coincided with the first stop of the tables and with the time of reaching surface. When ascent is controlled by the computer, the diver matches his actual depth with the ascent depth at all times. An ascent controlled in this way will result in a continuous ascent curve of compound exponential form.

The computer was therefore expected to reproduce the 'safety' of the tables with some saving in decompression time, because of the greater efficiency of the continuous ascent profile. Since diffusion proceeds continuously, the decompression solution of any subsequent change in ambient pressure will be presented continuously.

The first practical dives were simulated in a hyperbaric chamber, to permit more precise experimental control and data recording for direct comparison with similar dives controlled by decompression tables as reported elsewhere (Des Granges 1956; *Admiralty Experimental Diving Unit Report* 1962; Adolfson 1964). Ascent from all dives was dictated by computer information depth being adjusted by the divers in the chamber or occasionally by outside control. Ascent profiles were recorded by barographs. Initially, no particular attempt was made to limit exercise at any time of the dive. As experience and confidence was gained, moderate sporadic exercise was encouraged to stimulate more closely work at depth during the ascent and on immediately reaching the surface. No significant effect was noted on the incidence of 'bends'.

The classification of decompression sickness conforms to that of Golding, Hempleman, Paton and Walder (1960). Thus Type I refers to pain only and manifestations related to the skin and lymphatic system and Type II to central nervous system and respiratory involvement. All signs and symptoms, however slight, were recorded and treated by recompression.

The exposures to pressure are divided into two classifications, single and repetitive:

1. *A single dive* is one in which no previous exposure to pressure has been experienced in the preceding 18 hours.
2. *A repetitive dive* is one in which previous exposure to pressure has occurred within the preceding 18 hours.

The single and repetitive types of exposure can be carried out with linear or random profiles:

1. *A linear profile* is one in which the exposure to pressure is a linear function of time. These are the classical dives tabulated in the USN 1958 Decompression Tables.
2. *A random profile* is one in which the exposure to pressure is a non-linear function of time.

The initial rapid phase of the ascent was at 60 ft/min (1·8 ATA/min) until the ascent depth specified by the computer was reached. This depth corresponded closely with the depth of the first stop of the appropriate table. Thereafter, the continuous ascent profile generated by the computer was followed until the surface was reached. Fig. 16.1 shows such a 'classical' dive.

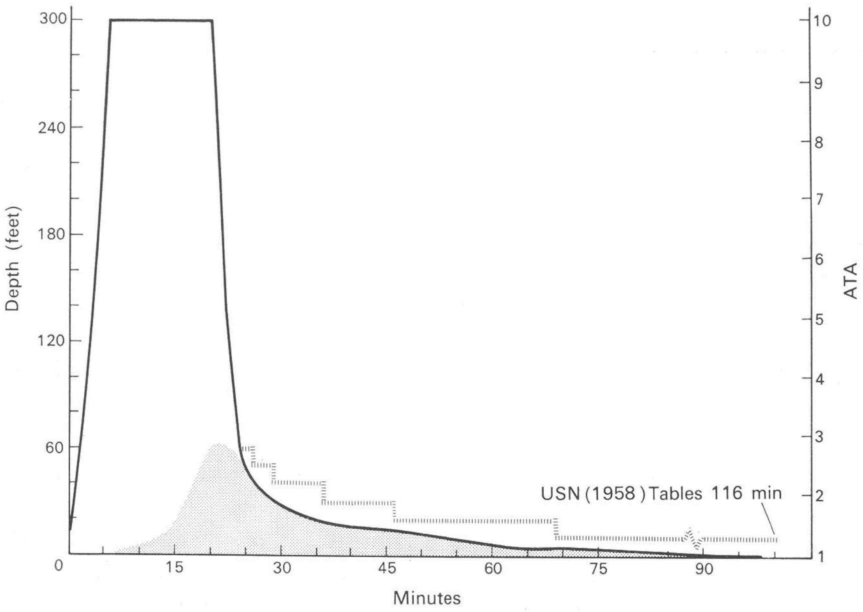

FIG. 16.1. Classical single dive

The ascent depths generated by the computer throughout the dive and followed when controlling ascent are shown as the shaded area. The shape of the decompression path is of a compound exponential type. The decompression schedule specified by the USN 1958 Tables is given for comparison.

The continuous ascent path derived from the Mk II P computer saves 15% to 35% in decompression time compared with that specified by the USN 1958 Tables. The percentage of time saved is a function of the depth–time configuration of the dive.

In practice, classical dive profiles rarely occur. For this reason, many dives classified as single dives followed an irregular pattern as might be required by a complex operational dive.

Since the actual pressure–time history, however complex it might be, determines the safe ascent pressure or depth displayed by the computer, the only effect of following an ascent path which is deeper than indicated will be to prolong the decompression. When testing the validity of the decompression solution, it is essential to arrive at the surface at precisely the same time as the ascent depth indicates this to be safe. It was often convenient, especially in actual dives, to ascend in accordance with computer information to about 10 ft, remaining there until the computer indicated ascent to the surface. Fig. 16.2 illustrates such a dive. Two-hundred and seventy-three dives of this single-exposure type were carried out by 39 subjects with ages ranging from 22 to 44 years over a range of depths from 40 ft (2·2 ATA) to 300 ft (10·1 ATA) and for durations of 10 to 360 min with a 'bends' incidence of 3·5%.

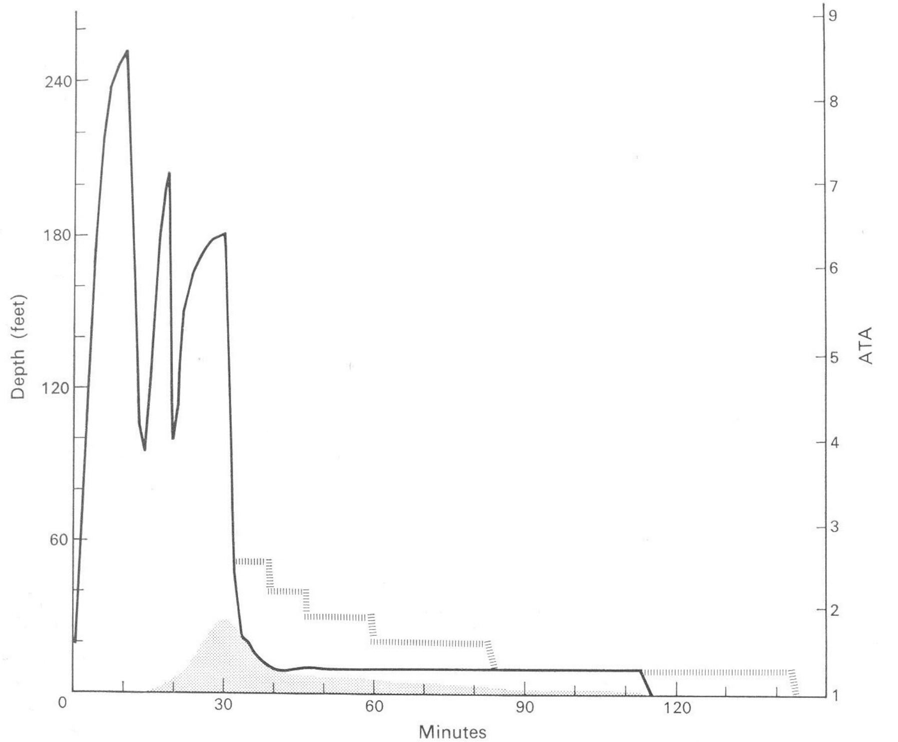

FIG. 16.2. 'Random' dive

The abrupt changes in depth during the dive deliberately exaggerate the variability of a typical dive, and while treated as a single dive, show some of the characteristics of a repetitive dive. The ascent depth specified by the computer is shown by the shaded area and compared with the decompression schedule of the tables.

The next series of dives was designed to test the performance of the computer in controlling repetitive dives and thus explore the validity of that most useful feature, a memory of previous events. In most cases the dives were carried out well beyond the limits specified by the USN 1958 Repetitive Tables, since the initial dives were to depths in excess of 190 ft (6·8 ATA). As many as six successive dives were made with surface intervals ranging from 10 min to 10 hours. In order to accelerate the accumulation of experience in some dives the intervals between successive dives were reduced to a minimum (Fig. 16.3). In such cases some subjects were brought to the surface when indicated by the computer and remained there to act as controls. This tested the validity of the decompression solution for that dive. The remaining subjects continued the repetitive series to test the subsequent and final decompression solutions. Two-hundred and fifty repetitive dives were carried out by 12 subjects over a range of depth from 10 ft (1·3 ATA) to 250 ft (8·6 ATA) and for durations of 10 min to 12 hours with a 'bends' incidence of 7%.

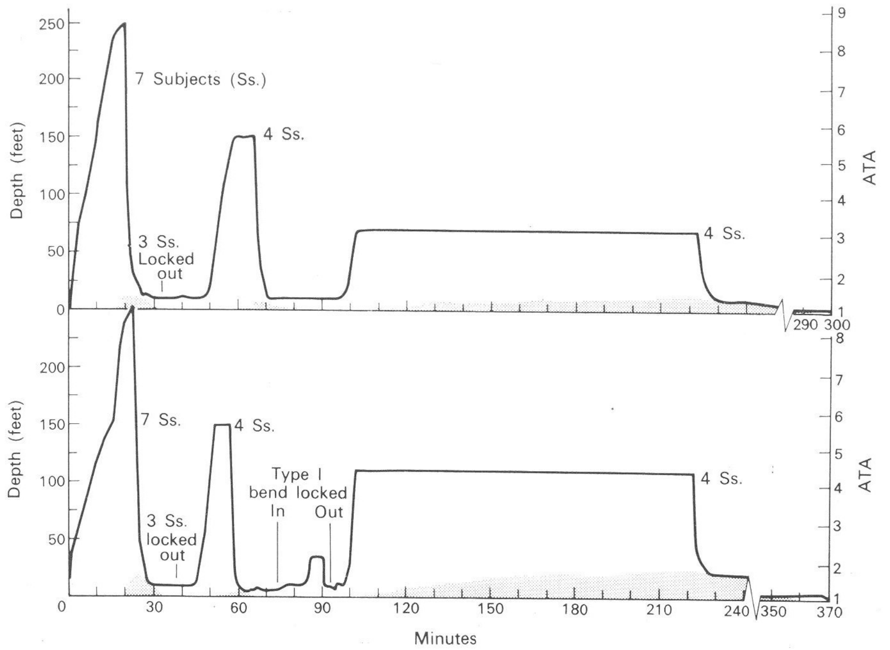

FIG. 16.3. Repetitive dives

In the two examples shown, the effectiveness of the computer ascent data was tested by 'control' subjects surfaced after the first dive only. In the case of the dive illustrated by the lower graph, one subject presented with a Type I 'bend' half an hour after surfacing. He was treated on 100% oxygen using the early therapeutic tables suggested by Workman and Goodman (1965), as shown (while the remaining four subjects breathed air) then surfaced when treatment was completed. Thereafter the remaining four subjects dived to 112 ft (4·4 ATA) for 2 hours to complete the series without incident.

Multiple dives were carried out during which the ascent from each dive was deliberately shallower than the computer ascent depth with the object of provoking cases of decompression sickness in order to test the validity of the 'threshold' concept. An example of this is shown in Fig. 16.4. Seven subjects made 91 dives of this type of which 19% resulted in manifestations of decompression sickness.

The most stringent constants obtained from the analysis shown in Table 16.1 were selected to permit computation as close as possible to the limiting 'bends' threshold for man. It was anticipated that these constants would be inappropriate for long exposure times at depth, since as shown in Fig. 16.5, the ratios appear to decrease as exposure times are increased. It was difficult to determine whether these ratios actually decrease or whether they appear to decrease due to the inappropriate selection of half-times and 'tissue' compartment configuration. It was also difficult to understand why different supersaturation ratios should be involved. Therefore an analysis was made to determine the half-times required for a

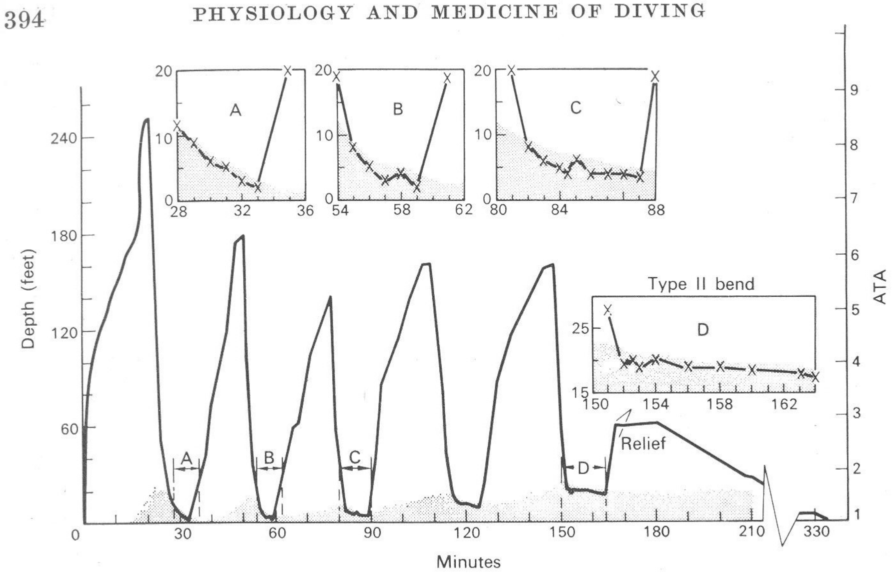

FIG. 16.4. Repetitive dives designed to provoke 'bends'

In this sequence the actual ascent profile from each dive was intentionally shallower than specified by the computer by a few feet. A Type II bend presented during ascent from the fifth dive. This subject only was given 100% oxygen while treatment pressure was applied as shown. Final ascent for the remaining subjects was controlled by computer in the normal manner. It should be noted that the slope of the ascent path for each successive dive becomes less steep as the total time increases, an indication of the lengthening time constant of the controlling compartment. In a series of dives of this type one can explore in turn the parameters of inert gas elimination from the fastest to the slowest component.

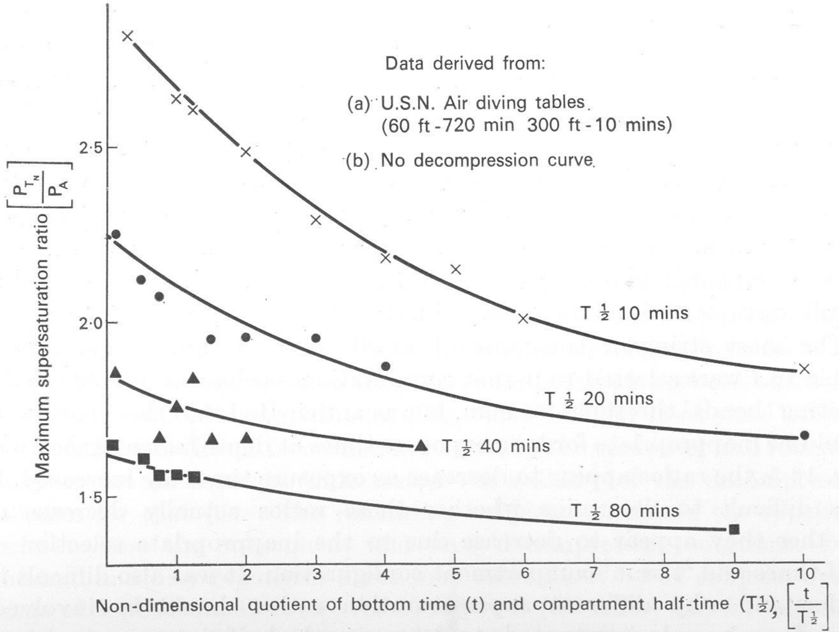

FIG. 16.5. Variation of ratio with saturation

parallel computer configuration which would satisfy a common ratio for all compartments.

A parallel pneumatic analogue computer, designated Mk III P was constructed with half-times of 20, 40, 80 and 160 min with a common inert gas supersaturation ratio (P_{T_N}/P_A) of 1·6 : 1 to test this analysis. With this computer 478 single and repetitive dives were made by 15 subjects over a range of depths from 30 ft (1·9 ATA) to 260 ft (8·9 ATA) and for durations of 15 to 240 min with a 'bends' incidence of 1·5%.

While the parallel analogue configuration of diffusion compartments has empirical justification in man, physiologically the transfer of gas between the lungs and the remote tissues can be visualized as a series or a series-parallel system of diffusion gradients.

A detailed mathematical analysis was conducted on the series configuration. This analysis showed that a good fit to the nil decompression curve (Van der Aue, Keller, Brinton, Barron, Gilliam & Jones 1951) was obtained with a minimum of four series compartments each having a 21-min half-time with a ratio (P_{T_N}/P_A) of 1·6 : 1 being applied to the first compartment only in order to provide computer readout. Since this concept gave promise of great simplicity in design and calibration, a number of series computers designated the Mk IV S were constructed to evaluate the limits inherent in this particular system. This series arrangement effectively increases the time constant of the first compartment with time.

The decompression profile generated by the Mk IV S computer gave a safer ascent than that derived from the original Mk II P, for exposures less than 3 hours in duration. The computer contained the information for safe decompression from exposures longer than 3 hours within its other compartments. The next logical step was taken in which a common ratio was applied to each of the four compartments in a series configuration. The computer readout was derived from that compartment having the highest pressure and presented a safe ascent depth on the same scale as the ambient depth. In order to increase the margin of safety further, the lowest ratio (P_{T_N}/P_A) of 1·44 : 1 obtained in the analysis illustrated in Fig. 16.5 was selected.

Such a computer, designated the Mk V S shown in Figs. 16.6 and 7, was calibrated with four compartments each with a half-time of 21 min and a common ratio of 1·44 : 1. Thus calibrated, this configuration will have an effective terminal half-time of 172 min, which is 8·25 times an individual compartment half-time (Stubbs & Weaver 1965). Examples of dives using this configuration are shown in Figs. 16.8 and 9.

Many experiments of this type provided a double check of the adequacy of the decompression solution. If decompressions from the later exposures are without incident, it is probable that the preceding decompressions must

FIG. 16.6. Prototype Mk V S computer
With pressure case removed to show dial pointers and Bourdon tube assembly.

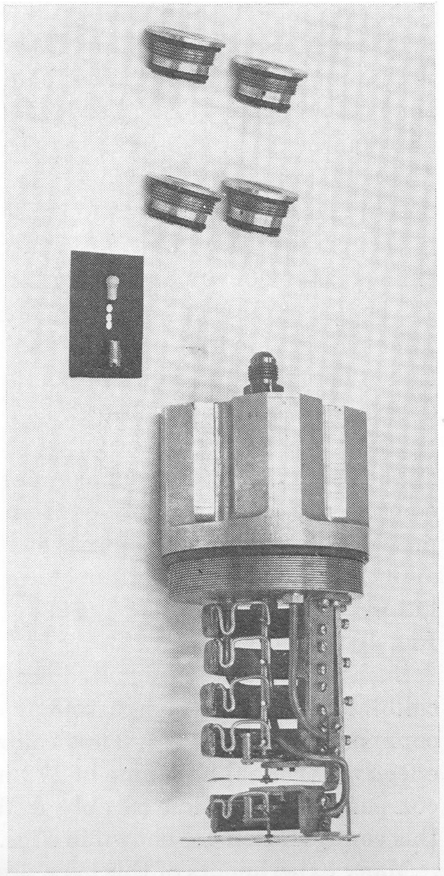

FIG. 16.7. Prototype Mk V S Computer
With volume plugs and a single pneumatic resistor disassembled.

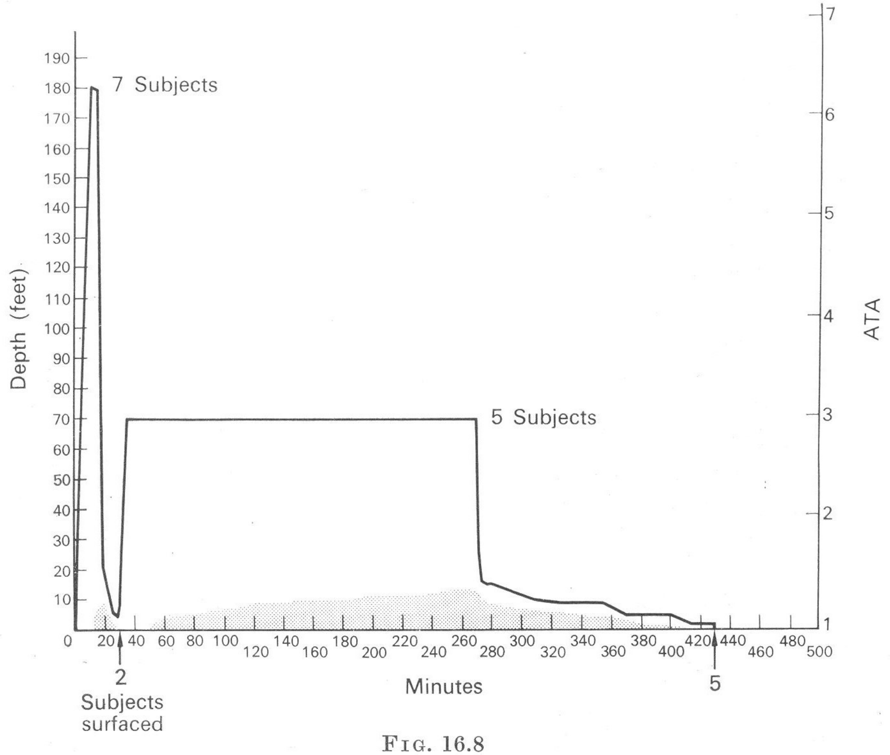

FIG. 16.8
In this experiment two dives were carried out in succession. The safe ascent depth is shown throughout by the depth of the shaded area. The first dive with seven subjects was made to a depth of 180 ft (6·5 ATA) for 15 min. When the computer ascent depth indicated sea level, two subjects were 'locked out' directly to the surface to act as controls. The remaining five subjects carried out the second dive to 70 ft (3·1 ATA) for 4 hours, finally surfacing precisely in accordance with computer information. Each dive was symptom free.

be of equal validity. Other repetitive dives were made with surface intervals ranging from 10 min to 12 hours.

A total of 3775 single and repetitive dives using 111 subjects with ages from 18 to 45 years have been carried out over ranges of depth of 30 ft (1·9 ATA) to 250 ft (8·6 ATA) for a duration of 15 min to 4 hours with a 'bends' incidence of 0·6%. Figs. 16.10 and 11 show the range of dives covered with computers Mk III P, Mk V S and Mk VI S.

A summary of results of various computer configurations for air diving is shown in Table 16.2:

AUTOMATIC CONTROL OF HYPERBARIC CHAMBERS

A pneumatic analogue decompression computer was designed to provide a visual record and an automatic control for hyperbaric chambers. This computer controller designated the Mk VI S shown in Figs. 16.12, and

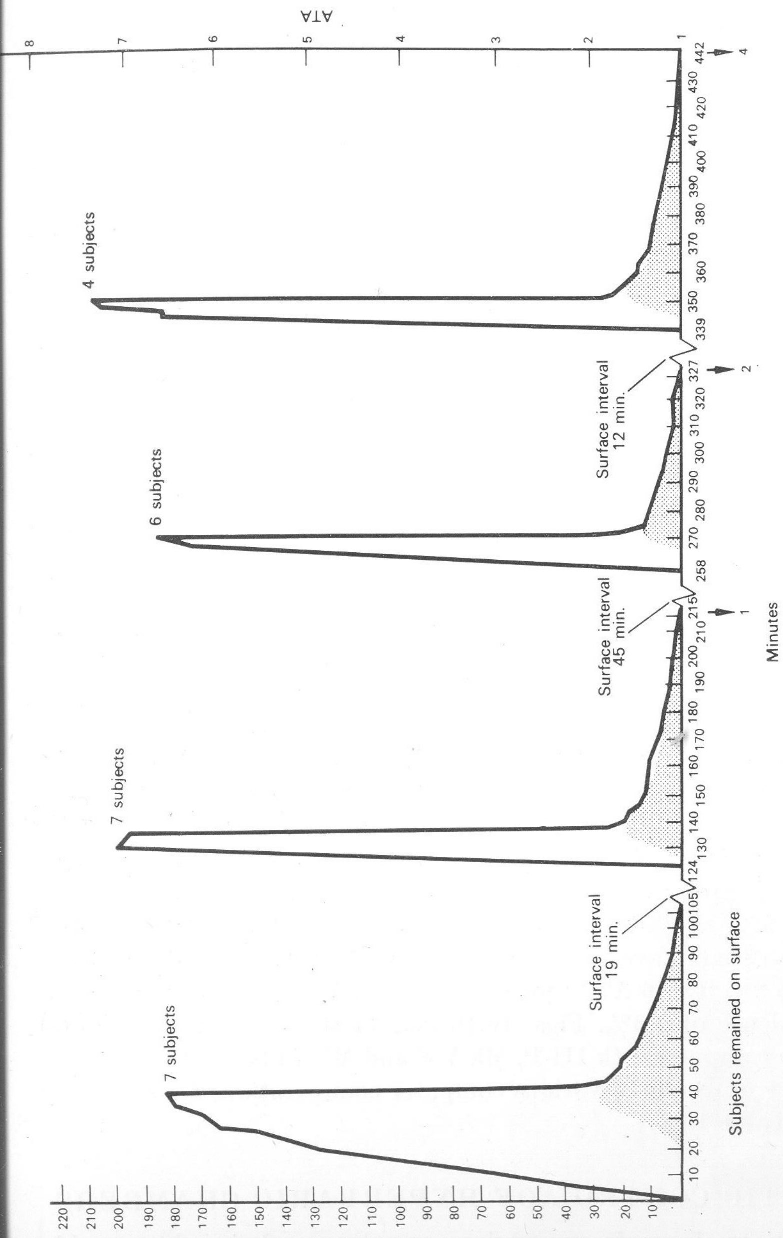

Fig. 16.9

In this sequence of repetitive dives, seven subjects carried out the first random dive to 183 ft (6·5 ATA). After a surface interval of 19 min, the same seven subjects carried out a second random dive to 198 ft (7·0 ATA). Following a second surface interval of 43 min, six of the subjects made a third random dive to 186 ft (6·6 ATA). The seventh subject remained at the surface to act as control. On completion of this dive, two subjects remained at the surface. After a third surface interval of 12 min, the remaining four subjects carried out a random dive to 210 ft (7·4 ATA). As in previous exposures, the ascent to surface again closely followed computer ascent information. No symptoms were noted by any of the subjects.

Table 16.2

Pneumatic Analogue Decompression Computer. The incidence of 'bends' during trials July 1963 to August 1967, single and repetitive dives with compressed air

Model	*Type of computer*		
	Mark II P	*Mark III P*	*Mark V S & VI S*
Compartment configuration	4 Parallel	4 Parallel	4 Series
Half-time (min)	10 20 40 80	20 40 80 160	21 (common to all compartments)
Supersaturation ratio (P_{T_N}/P_A)	2·65 2·15 1·85 1·65	1·6 (common to all compartments)	1·44 (common to all compartments)
Scope of dives	10·1 ATA— 20 min 3·1 ATA—12 hours	8·6 ATA—80 min 5·5 ATA— 4 hours	
No. of subjects	39	15	111
Range of ages	22 to 56	19 to 47	18 to 45
No. of dives	523	478	3775
Decompression sickness *Type I* *Type II*	 20 6	 5 2	 17 5
Percentage incidence	5·0	1·5	0·6

16.13 is identical in principle of operation, configuration and calibration as the Mk V S diving computer described above. The computer is constructed within the framework of a standard (Taylor) two-pen pneumatic pressure recorder. The four volume-resistor components are mounted externally to the framework. Bourdon tubes are provided for pressure readout of each compartment. The Bourdon tube linkages are provided with zero set and ratio adjustments and a mechanical comparator linkage permits the read-out and recording of the critical ascent depth. A fifth Bourdon tube senses and records ambient pressure. A mechanical-electrical device which operates between the ambient depth and ascent depth indicators provides an error signal for control purposes.

A MINATURE PNEUMATIC ANALOGUE COMPUTER

A miniature version of the pneumatic analogue decompression computer, having the same configuration and constants as the Mk V S is under development, using synthetic plastic materials. The pressure in each of five transparent tubes sealed at one end is indicated by the position of

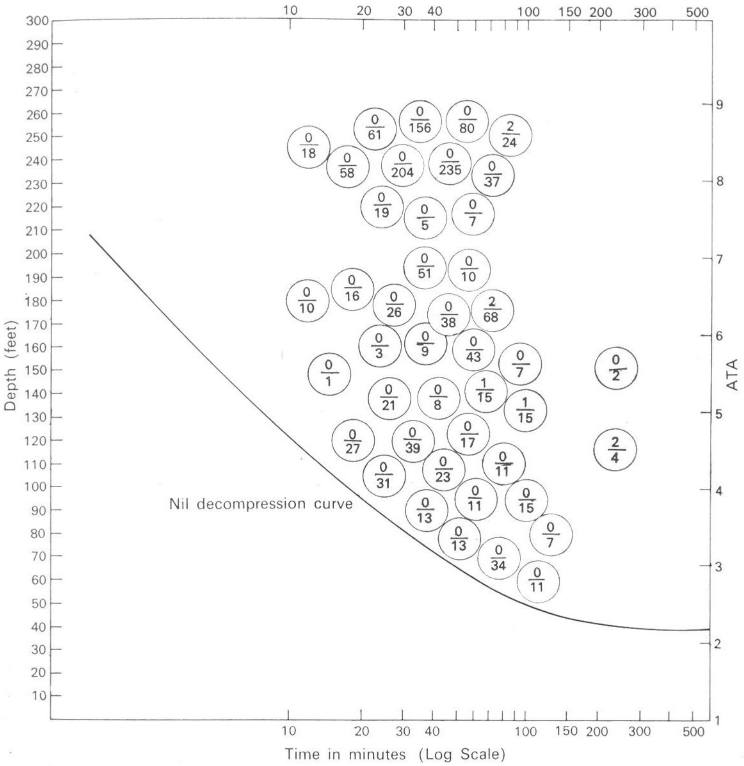

FIG. 16.10. Range of single dives—Mark III P, V S and VI S computers March 1965 to August 1967. Numerator = bends; denominator = exposures

mercury pistons, of which one tube always indicates ambient pressure and the remaining four tubes are connected in series via pneumatic resistors. This system dispenses with Bourdon tubes and mechanical linkages and provides compact readout with scale expansion near the surface and at altitude, where accuracy during decompression is most desirable. The mercury pistons in each of the four compartments are located during assembly so that the trapped volume, relative to that in the ambient pressure tube, corresponds to the supersaturation ratio. Thus the ascent depth of each compartment is always indicated. Decompression is controlled by reducing ambient pressure so that the ambient tube piston does not pass any of the compartment pistons.

OXYGEN–HELIUM DECOMPRESSION

Theoretical considerations (U.S.N. Oxygen–helium Tables 1958; Stubbs & Weaver 1965) suggested that the decompression profile following an exposure to pressure while breathing an oxygen–helium mixture should be different from that derived for the same exposure to an oxygen–nitrogen mixture such as air. The ascent depth generated by the pneumatic analogue decompression computer following an exposure to pressure is dependent upon the depth–time course and the physical constants of the gases involved. Bench tests had indicated, within the limited scope of the data available, that the appropriate decompression profile for an exposure to a 20% oxygen and 80% helium mixture would be provided by a computer calibrated for air diving.

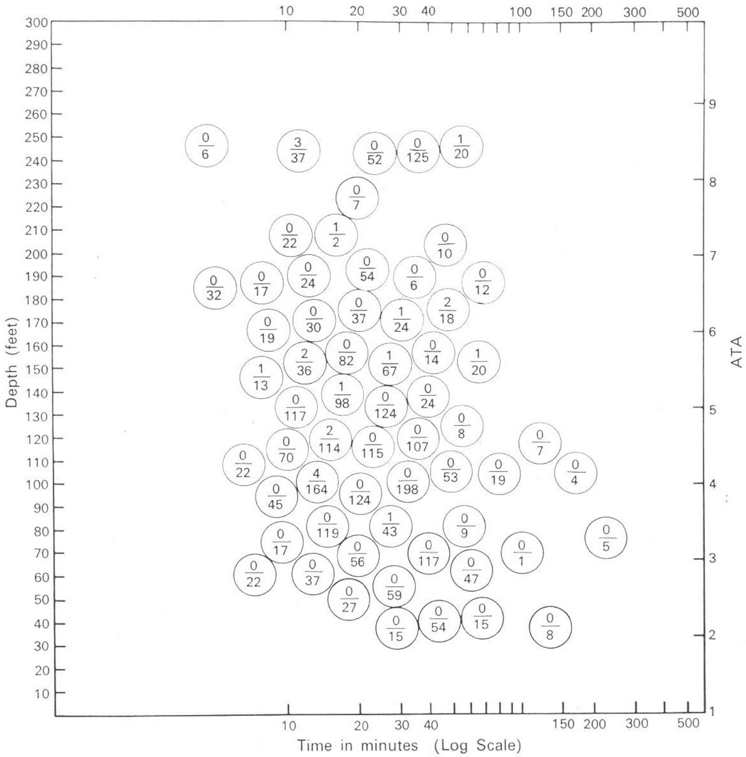

FIG. 16.11. Range of repetitive dives—Mark III P, V S and VI S computers March 1965 to August 1967. Numerator = bends; denominator = exposures

A series of dives was made in a hyperbaric chamber pressurized by compressed air during which subjects respired from a built-in breathing system supplied with an oxygen–helium mixture. Computers, monitoring the pressure-time history of the oxygen–helium atmosphere which the subjects were breathing, provided the ascent information used to control decompression. Other computers monitored the chamber atmosphere, thus providing a simultaneous comparison of the ascent profiles for oxygen–

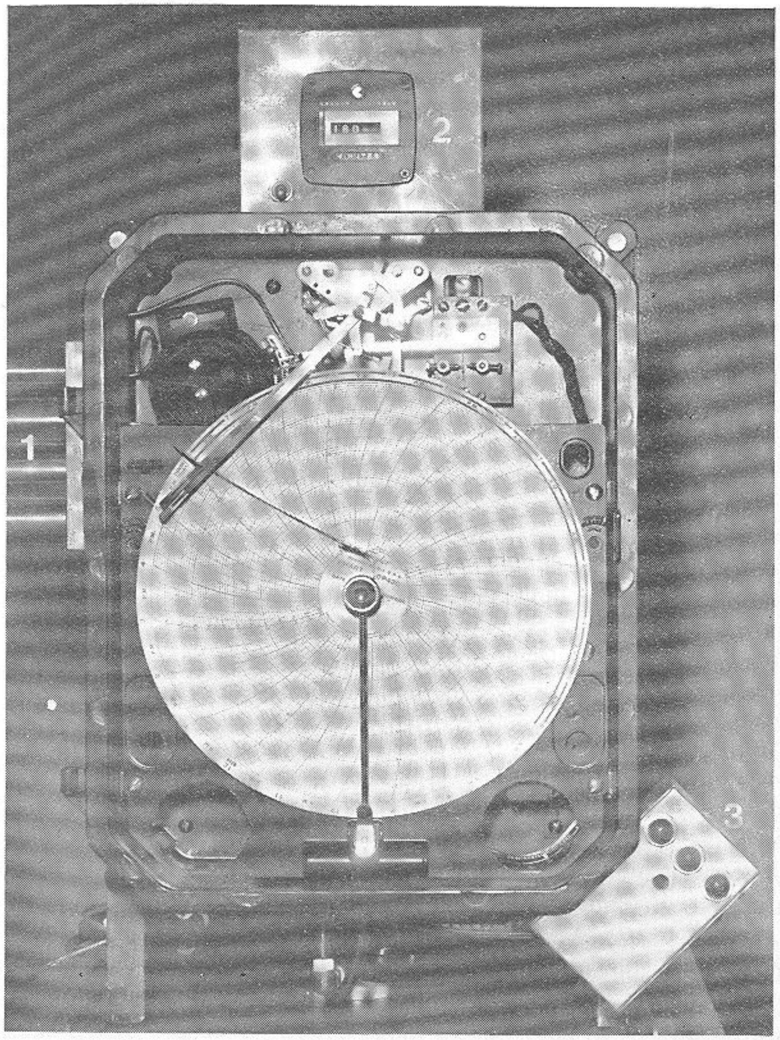

FIG. 16.12. Prototype Mark VI S pneumatic analogue computer

1. Four volume-resistor components connected in series.
2. Elapsed time clock.
3. Visual warning from error signal.

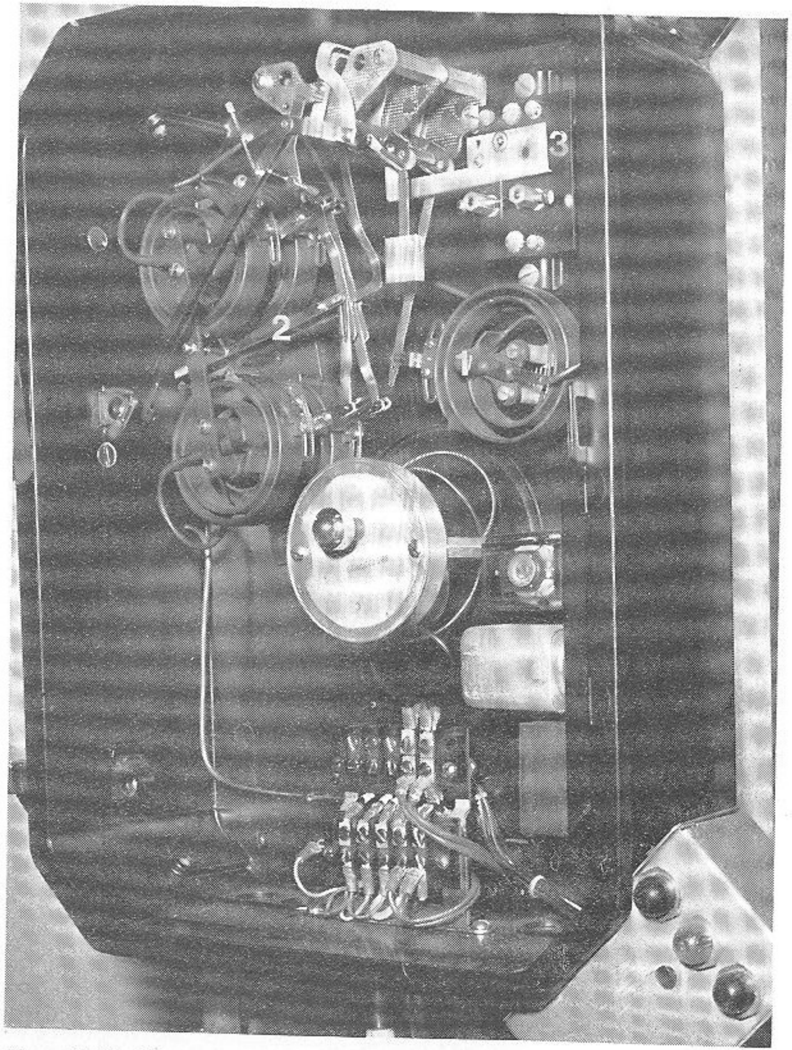

FIG. 16.13. Prototype Mark VI S pneumatic analogue computer, with chart plate removed

1. Ambient pressure Bourdon tube linked to first pen.
2. Four Bourdon tube assembly with pressure comparator linked to second pen.
3. Micro-switch giving error signal.

nitrogen and oxygen–helium mixtures. The successful decompression following these oxygen–helium dives confirmed the laboratory predictions.

A comparison of the decompression profiles generated by the computers for a random profile dive to a maximum depth of 245 ft (8·4 ATA) for 33 min for oxygen–helium and air breathing is shown in Fig. 16.14.

In the next series of exposures, the pneumatic analogue computer was used to determine the appropriate decompression when changes were made

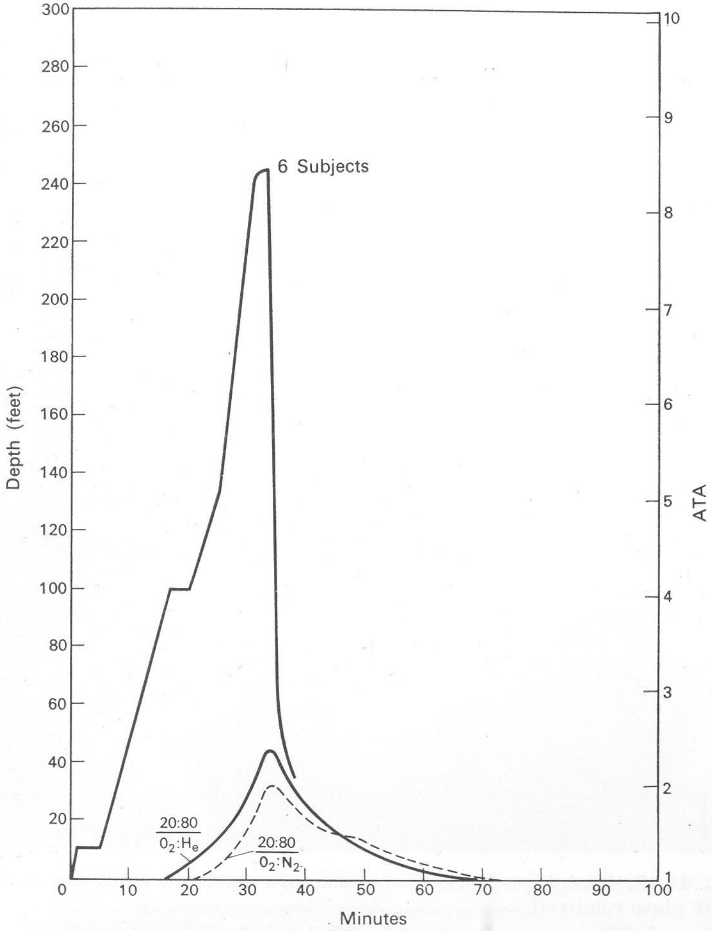

FIG. 16.14. Single oxygen–helium dive

Six subjects carried out a random profile dive to a maximum depth of 245 ft (8·4 ATA) for 33 min breathing a 20% oxygen and 80% helium mixture. Actual ascent, dictated by a pneumatic analogue computer sensing this inspired gas, is shown by the solid line. A second identical computer monitored chamber air and the equivalent ascent profile had air been breathed is depicted by the broken line for comparison. No sequelae were noted from this exposure.

in the inert gas during successive dives. Repetitive dives were carried out on oxygen–helium, followed by one or more air dives. Other sequences commenced with air dives, switched to a series of oxygen–helium dives followed in turn by one or more air dives (Fig. 16.15).

Two-hundred and fifteen oxygen–helium dives and 178 air dives were carried out in this series by 19 subjects over a range of depths from 50 ft (2·5 ATA) to 250 ft (8·6 ATA) and for total durations of 10 to 90 min with a 'bends' incidence of 1%.

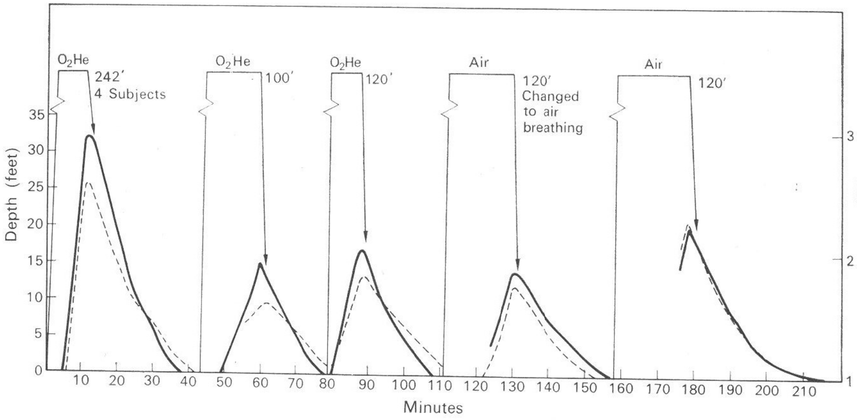

FIG. 16.15. Sequence of oxygen–helium and air dives

Four subjects carried out a 242 ft (8·3-ATA) dive for 12 min breathing 20% oxygen and 80% helium, ascent controlled by a pneumatic analogue computer sensing inspired gas. Shortly afterwards two repetitive dives to 100 ft (4 ATA) for 17 min and 120 ft (4·6 ATA) for 9 min breathing same mixture were made. At 111 min elapsed time all subjects disconnected from oxygen–helium supply and breathed chamber air. Two more repetitive dives were then carried out to 120 ft (4·6 ATA) for 19 min and to 120 ft (4·6 ATA) for 21 min, decompression from each dive was controlled by the same computer now exposed to air. The actual ascent profiles are shown in solid line. For comparison, the ascent profile from an identical computer monitoring the equivalent air history throughout is shown by the broken line. No sequelae were noted from this series.

THEORETICAL CONCEPTS

Asymmetry

The construction of early decompression tables was based on the assumption that the processes of inert gas uptake and elimination were linear and hence symmetrical. Hempleman (1960) produced evidence in animals that strongly suggested that these two processes were not symmetrical. The need for empirical correction of the earlier diving tables over the years may be attributable to a similar mechanism occurring in man. Following prolonged or complicated dive profiles, it was found that the solution offered by the pneumatic analogue computers differed significantly from that derived from linear mathematical or electrical analogues which treat the problem as if inert gas exchange were a symmetrical process.

The *in vivo* trials with the pneumatic computer left no doubt that its inherent asymmetry was operating in the same sense as that presumed to occur in man. The continuous ascent profile generated by the computer can never be faster or shallower than that generated by a symmetrical analogue. In general it will be slower and deeper.

In the laboratory the differences between a linear and non-linear system can be accentuated by comparing the response of each system to a step input. This method constitutes a stringent calibration test for the computer. The duration of the step input is chosen to be sufficiently long to insure that all computer compartments play a part in the response characteristics. The response of the ascent depth indicator of the pneumatic computer to such a step exposure of oxygen was significantly different to the response predicted by the symmetrical system (see Fig. 16.16).

This asymmetrical response of the pneumatic computers is due to the non-linear flow characteristic of the pneumatic resistors and their sensitivity to the pressure to which they are exposed (Stubbs & Weaver 1965).

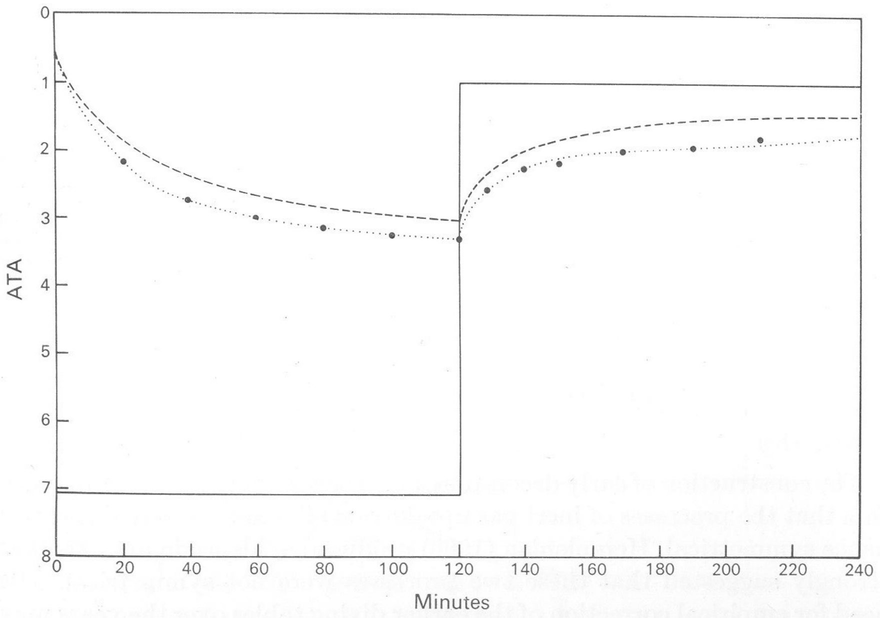

FIG. 16.16

The transient response of the ascent depth indicator of a Mk V S pneumatic computer is compared with the responses of two theoretical models. The pneumatic computer values are shown as large dots, the response of a linear system with the same configuration and system parameters as a dashed curve, and the response of a non-linear system based on slip flow (generated independently by an E.A.I. TR48 analogue and an I.B.M. 360 digital computer) by a dotted curve. Each system was subjected to a step input equivalent to 200 ft (7·07 ATA) for 120 min (solid line). The estimated probable error in the experimental values is approximated by the diameter of the large dots.

In Fig. 16.17 is illustrated the steady state flow characteristic of a typical pneumatic resistor used in the computers for various gases and gas mixtures.

The non-linearity of porous media

The manufacturer (Sartorius) states that the material used for these pneumatic resistors consists of a microscopic mesh of synthetic fibres having a mean pore diameter of the order of 5×10^{-6} cm (0·05 μ). The flow of a gas through such porous media has been described classically by Carman (1956) as occurring in three distinct but smoothly connected regimes. The regime in which the gas flow occurs and the theoretical expression which describes the flow depends upon the ratio of the mean free path, λ, of the gas to the mean pore diameter, d_e, of the porous medium.

Free molecular flow

Free molecular or Knudsen flow occurs for $\lambda/d_e \gg 1$. This is a diffusion process in which the mean free path of the gas molecules is so large in

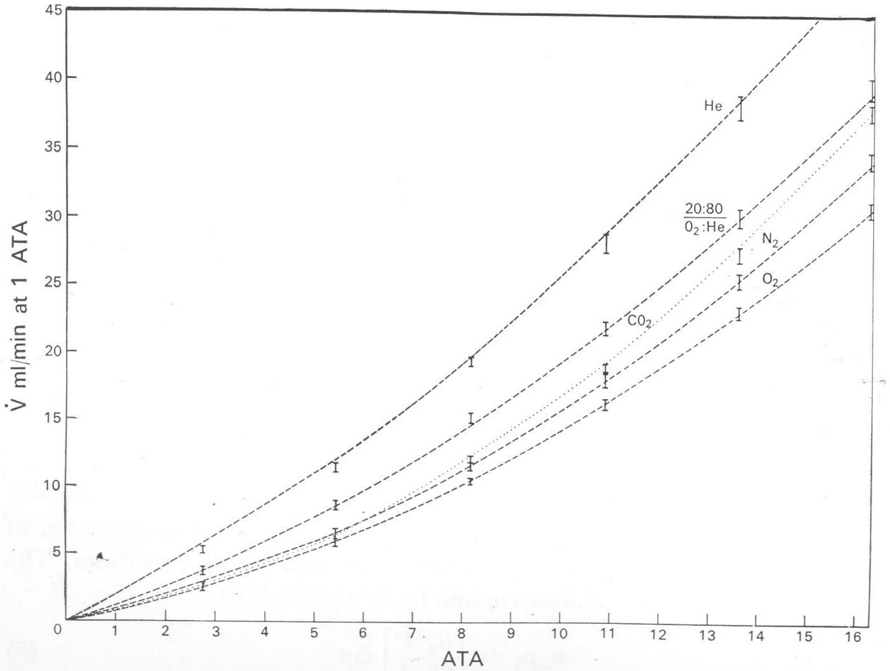

FIG. 16.17

The theoretical and experimental values of steady state volume flow through a typical Mk V S pneumatic resistor for various gases and gas mixtures. The theoretical values for helium, oxygen–helium, nitrogen and oxygen are shown as dashed curves, the theoretical values for carbon dioxide are shown as a dotted curve. The theoretical values were obtained from slip flow theory. The estimated probable error in the experimental values is approximated by the error bars.

relation to the mean pore diameter, that the probability is much greater for energy exchange between the gas molecules and the walls of the porous medium, than between each other. This flow is linear with the pressure differential of the gas across the medium and may be described by the relation

$$u_1 p_1 = \left[\frac{1}{3}\frac{d_e}{L}\,\bar{v}\,\frac{(2 - f_0)}{f_0}\right]\Delta p \qquad (3)$$

where u_1 = linear velocity of the gas pressure p_1,
p_1 = absolute pressure of the gas at one face of the resistor at which u_1 is measured,
d_e = mean pore diameter of the porous medium,
L = length of the porous sample in the direction of flow,
$\bar{v}$ = mean thermal velocity of the gas molecules,
f_0 = fraction of diffuse collisions with the walls for Knudsen flow,
Δp = pressure difference across the medium equals $p_1 - p_2$,
p_2 = gas pressure on the other face of the resistor.

Slip flow

Slip flow occurs as λ/d_e approaches unity, in this case the probability that the gas molecules exchange energy with each other increases. This flow is non-linear with pressure differential across the medium and may be described by the relation

$$u_1 p_1 = \left[\frac{d_e^2\bar{P}}{32\eta L} + \frac{d_e}{4L}\sqrt{\frac{\pi RT}{2M}}\left(\frac{2 - f_1}{f_1}\right)\right]\Delta p \qquad (4)$$

where $\bar{P}$ = mean pressure of the gas in the porous medium = $(p_1 + p_2)/2$,
η = viscosity of the gas,
R = gas constant,
T = absolute temperature of the gas,
M = molecular weight of the gas,
f_1 = fraction of diffuse collisions with the walls for slip flow.

Viscous flow

Viscous flow occurs as $\lambda/d_e \ll 1$, the gas molecules exchange more of their energy with each other than with the walls of the medium. The expression describing this flow regime is

$$u_1 p_1 = \left[\frac{d_e^2\bar{P}}{32\eta L}\right]\Delta p \qquad (5)$$

Steady state slip flow

The mean free path of oxygen and nitrogen at sea level pressure is of the order of 10×10^{-6} cm. Then the ratio $\lambda/d_e \div 2$ for the porous medium of the typical pneumatic resistor under discussion. In the pneumatic analogue computers, gas flow should occur in the slip flow regime over a considerably wide range of ambient pressure. To determine the validity of the preceding statement, the observed steady state flow characteristic of a pneumatic resistor is compared with slip flow theory for several gases and gas mixtures. The slip flow equation (4) may be expressed in terms of volume flow, $\dot{V}_1$, as follows:

$$\dot{V}_1 = \frac{\pi d_e^4 N}{256 L p_1}(p_1 - p_2)\left[\frac{16}{d_e}\left(\frac{2 - f_1}{f_1}\right)\sqrt{\frac{\pi RT}{2M}} + \frac{(p_1 + p_2)}{\eta}\right] \qquad (6)$$

where $\dot{V}_1$ is in ml/sec,
d_e is in cm,
η is in poise or dynes-sec/cm^2,
L is in cm,
M is in gm^2/mole,
p_1 and p_2 are in dynes/cm^2,
R equals $8{\cdot}31 \times 10^7$ ergs/°C mole,
N is the number of pores in the medium through which the gas flows,
T is in degrees Kelvin,

for p_1 and p_2 in ATA; $f_1 = 1$; and $\dot{V}_1$ in ml/min

$$\dot{V}_1 = 7{\cdot}46 \times 10^5 \frac{N}{L}\frac{d_e^4}{p_1}(p_1 - p_2)\left[\frac{0{\cdot}18}{d_e}\sqrt{\frac{T}{M}} + \frac{(p_1 + p_2)}{\eta}\right] \text{ ml/min} \qquad (7)$$

The values of N/L and d_e may be obtained for a given resistor experimentally for a given gas in conjunction with equation (7).

For a typical pneumatic resistor used in a Mk V S computer, the following values were determined.

$$N/L = 7{\cdot}52 \times 10^8 \text{ cm}^{-1}; \qquad d_e = 1{\cdot}25 \times 10^{-5} \text{ cm}$$

Then the slip flow characteristics of this resistor for any gas or gas mixture becomes

$$\dot{V}_1 = 1{\cdot}36 \times 10^{-5}\frac{(p_1 - p_2)}{p_1}\left[1{\cdot}45 \times 10^4\sqrt{\frac{T}{M}} + \frac{(p_1 + p_2)}{\eta}\right] \text{ ml/min} \qquad (8)$$

In Fig. 16.17, the measured values of $\dot{V}_1$ are compared with those predicted by equation (8).

It is of interest that the value of viscosity, η, and molecular weight, M, used to predict gas mixture flow in equation (8) were obtained by weighting these parameters of the constituent gases by their respective mole fractions. The gas mixture appears to flow through the resistor as a simple gas having these weighted parameters.

Transient slip flow

The asymmetrical response characteristics of a typical pneumatic resistor for oxygen, when coupled to a fixed volume V_2 of 25 ml may be seen in Fig. 16.18. With the volume initially at pressure p_i, a step input pressure p_1 is applied to the resistor. The pressure p_2 in the volume is plotted as a function of time. When p_2 reaches the value of p_1, the input pressure is reduced to p_i. p_2 is plotted as a function of time. The symmetrical response of a linear resistor-volume combination to the step input is shown for comparison in the same figure.

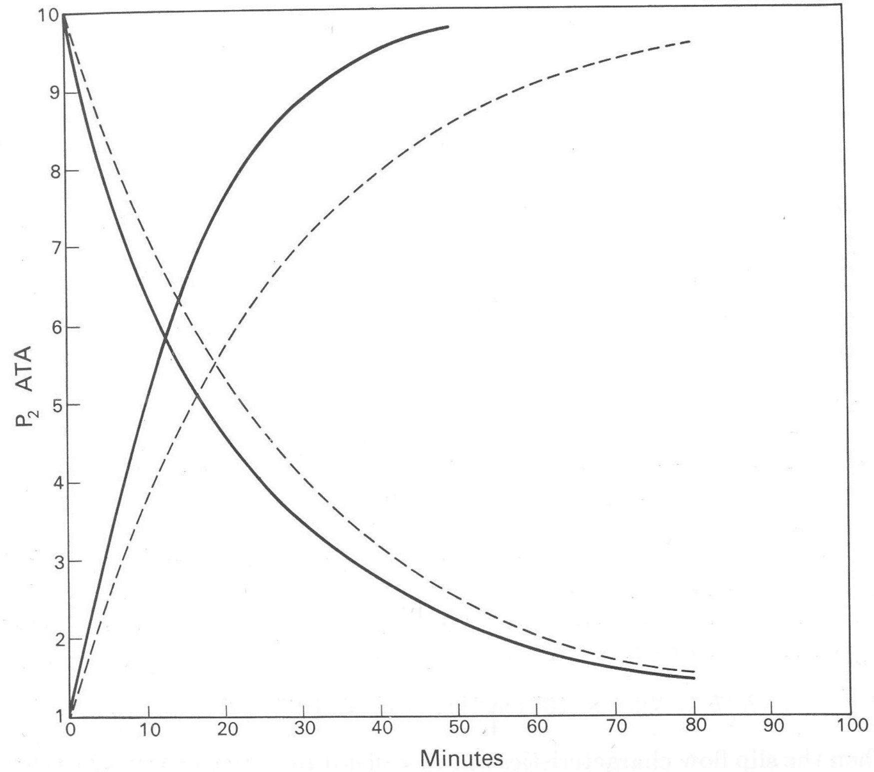

FIG. 16.18

The transient response of a typical Mk V S pneumatic resistor coupled to a 25 ml volume (solid curves) is compared with the response of a linear resistor coupled to the same volume (dashed curves). Each system is subjected to a step input pressure equivalent of 300 ft (10 ATA). The asymmetry of response is due to the non-linearity of the pneumatic resistor.

The expression predicting this asymmetrical transient response may be obtained from equation (8) and from the relationship expressing mass flow continuity; i.e.

$$\dot{p}_2 V_2 = p_1 \dot{V}_1 \qquad (9)$$

where p_2 is the pressure in volume V_2 at any time and $\dot{p}_2 = \mathrm{d}p_2/\mathrm{d}t$. Then

$$\dot{p}_2 = 1{\cdot}36 \times 10^{-5}\,\frac{(p_1 - p_2)}{V_2}\left[1{\cdot}45 \times 10^4\sqrt{\frac{T}{M}} + \frac{(p_1 + p_2)}{\eta}\right] \text{ATA/min} \qquad (10)$$

To determine the value of p_2 as a function of time equation (10) is integrated, with the initial condition that $p_2 = p_i$ for $t = 0$.

$$t = \frac{\eta V_2 \ln\left[\dfrac{(p_i - p_1)(p_2 + p_1 + 1{\cdot}45 \times 10^4\eta\sqrt{T/M})}{(p_2 - p_1)(p_i + p_1 + 1{\cdot}45 \times 10^4\eta\sqrt{T/M})}\right]}{1{\cdot}36 \times 10^{-5}(1{\cdot}45 \times 10^4\eta\sqrt{T/M} + 2p_1)} \text{ min} \qquad (11)$$

for pressures in ATA.

The response of a four-compartment series system of resistors and volumes cannot be expressed in such simple analytical form but can be written as four simultaneous non-linear differential equations for solution by a general purpose digital or analogue computer. The response of the pneumatic analogue computer of the Mk V S configuration to oxygen, compares favourably with the response obtained by an A.E.I. TR48 analogue computer and an I.B.M. 360 digital computer programmed with the pneumatic resistor relationships described above (Fig. 16.16).

Thus it is possible to predict the steady state flow, and the transient response of single- and multi-compartment systems consisting of the pneumatic resistors and fixed volumes for various gases and gas mixtures on the basis of slip flow theory. It is also possible to vary the degree of non-linearity of the pneumatic resistors by selection of mean pore diameter. The question now arises as to how non-linear the resistors should be to match the characteristics of the gas transfer mechanism in man.

A most useful piece of information to establish the quality and quantity of inert gas exchange might be derived from the measurement of actual uptake and elimination of a given inert gas in man when ambient total pressure is held constant. This information would determine whether the gas transfer mechanism is inherently non-linear or arises in diving practice from the concomitant ambient pressure reduction which can lead to cavitation.

ULTRASONIC DETECTION OF CAVITATION

In those experimental dives in which the 'bends threshold' was being explored by deliberately ascending shallow to computer information, an ultrasonic system measuring resonance absorption has been used on subjects, in an attempt to detect the onset of cavitation. A small but significant signal change (0·5 db) was observed during ascent when the inert gas tension computed by a Mk V S computer approximated ambient pressure, e.g. a ratio of 1 : 1 was exceeded. A strong signal change (7 db) was always observed prior to the occurrence of overt 'bends' symptoms, but there have been many instances of signal changes of the order of 3 to 5 db without a clinical case of 'bends' resulting.

SUPERSATURATION RATIO

This evidence would tend to suggest that cavitation occurs when supersaturation ratios greater than 1 : 1 are involved, but the cavitation may be asymptomatic. If a ratio of 1 : 1 were used, the resulting decompression would be safe but very long and economically restrictive. From the data presented here, a lower incidence of 'bends' occurs using computers set with ratios of 1·44 : 1 than for computers set with 1·6 : 1 for equivalent computer configuration and time constants.

Therefore, it is speculated that a probability function is involved relating symptoms to ratio and that for practical diving a compromise must be reached, trading a given increase in 'bends' incidence to achieve an acceptably lower decompression time. The Mk V S computer appears to offer a reasonable compromise.

ADVANTAGES OF THE COMPUTER

The pneumatic analogue computer has demonstrated some advantages in safety, decompression time and air supply economy over diving tables for decompression from single exposures. The great advantage of the computer, however, is in the provision of efficient decompression from random profile dives and repetitive exposures. Many of the dives described here would not have been practicable if controlled by tables, hence further comparisons are unjustified. Since an appropriate decompression profile is always available from the computer, regardless of the exposure, complicated diving operations can be carried out with considerable flexibility.

Multi-level and repetitive dives can be undertaken for example by a medical officer supervising the treatment of a patient in a hyperbaric facility without incurring a decompression debt longer than is strictly necessary.

When considering the relative merits of the compartment configuration of a computer, the series system has some advantages over the parallel system in that longer half-times can be achieved with less difficulty in resistor construction and calibration. A series configuration permits a closer fit to the nil decompression curve when a common ratio is applied to all compartments.

It does not appear to be necessary to consider different ratios for the computer compartments, particularly in a series system, in order to generate a safe decompression profile for man when diving within the practical pressure limits for air and for durations of less than 4 hours. The results obtained to date using computers to monitor oxygen–helium diving have been encouraging.

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