SECTION 7



SECTION 7

DECOMPRESSION ASPECTS

T R Hennessy

REVIEW

The 'standard' RN and AMTE(PL) decompression profile for deep saturation diving (shown in Table 1) was developed in the Deep Trials Unit (DTU) over a series of 67 oxy-helium experiments during 1971-74. The P_{O_2} was 0.22 bar up to Dive 51, and 0.4 bar thereafter(1,2). It was found that the higher P_{O_2} virtually eliminated frank decompression sickness symptoms that had routinely been occurring as the saturation depth was increased(3). Table 2 gives a summary of all 250 m exposures where the standard profile was used. Dives 66 and 67 included three one-hour excursions to 300 m, although the final decompression was from a 250 m state of saturation. Dive 60 was similar to Dives 66 and 67 but the final decompression began from 300 m after a therapeutic recompression following what appeared to be a vestibular incident at 250 m, 50 minutes after returning from the sixth 300 m excursion. However, complete saturation at 300 m would have been unlikely since only one hour was spent there before the final decompression.

The final decompression was an extrapolation of the 3 hours/5 m depth stages of the 250-175 m portion of the 250 m standard table (see Table 1).

Unfortunately Dive 67 proved to be the last DTU dive in excess of 200 m depth for the next four years, and at the time of writing, offshore use of the table to depths over 200 m has been very limited in both RN and commercial operations. The only other instances of using the 250 m table at PL were the 300 m dives, 5 and 6, in the Dry Chamber (DC) series and DTU Dive 81. These are shown in Table 3. Dives 4 and 10B were to lesser depths, but are included for completeness, since they were not symptom-free. The 300-250 m portion of the profile in all cases was the same extrapolation from 175 m as in Dive 67 above.

With the exception of DTU Dives 77 and 81, and DC Dive 10B, this was the background at the time that DC Dives 7 and 8 to 420 m were planned.

It was suggested that the 175 m profile could be extrapolated yet still further beyond 300 m to 420 m in view of the only minor niggles of Dives 5 and 6. [Evidently the apparent 'success' of the standard schedule to 300 m on P_{O_2} = 0.4 bar was at that time being measured against the failure of earlier schedules using the lower P_{O_2} = 0.22 bar.] However, by examining Tables 2 and 3 together, it can be seen that the standard profile and its extrapolations from 175 m are not at all free of minor symptoms, particularly on the last few drops to the surface. Clearly extrapolation to 420 m would be inadvisable until the offending feature of the profile had been identified, eg 5 m drops too large or too rapid, or average rates too fast.

TABLE 1 - AMTE(PL) 250 m SATURATION DECOMPRESSION TABLE*

Depth (m)	Elapsed Time on Leaving each Depth		Stop Time (hours)	Oxygen (%)	Depth (m)	Elapsed Time on Leaving each Depth		Stop Time (hours)	Oxygen (%)
	24-hr period	hours				24-hr period	hours		
250	0	0	-	1.54	120	3	17	4	3.08
245	0	3	3	1.57	115	3	21	4	3.20
240	0	6	3	1.60	110	4	1	4	3.33
235	0	9	3	1.63	105	4	6	5	3.48
230	0	12	3	1.67	100	4	11	5	3.64
225	0	15	3	1.70	95	4	16	5	3.81
220	0	18	3	1.74	90	4	21	5	4.00
215	0	21	3	1.78	85	5	2	5	4.21
210	1	0	3	1.82	80	5	7	5	4.44
205	1	3	3	1.86	75	5	12	5	4.70
200	1	6	3	1.90	70	5	17	5	5.00
195	1	9	3	1.95	65	5	22	5	5.33
190	1	12	3	2.00	60	6	3	5	5.71
185	1	15	3	2.05	55	6	8	5	6.15
180	1	18	3	2.10	50	6	13	5	6.67
175	1	21	3	2.16	45	6	19	6	7.27
170	2	1	4	2.22	40	7	1	6	8.00
165	2	5	4	2.28	35	7	7	6	8.89
160	2	9	4	2.35	30	7	13	6	10.00
155	2	13	4	2.42	25	7	20	7	11.43
150	2	17	4	2.50	20	8	3	7	13.33
145	2	21	4	2.58	15	8	10	7	16.00
140	3	1	4	2.67	10	8	17	7	20.00
135	3	5	4	2.76	5	9	0	7	25.00
130	3	9	4	2.86	0	Arrive Surface. Total decompression time: 9 days 5 minutes.			
125	3	13	4	2.96					

NOTES:
1. Ascent rate between 5 m stops to be at 1 m/min.
2. Ascent times are included in stop times.
3. Partial pressure of oxygen to be kept at 0.4 bar - except when approaching the 5 m stop, and thereafter to the surface, where the oxygen percentage should not be allowed to exceed 25%.

*Reproduced from Table 5, Oxy-helium saturation diving tables: CIRIA Underwater Engineering Group, Report UK11, 1978.

TABLE 2 - SUMMARY OF ALL 250 m SATURATION EXPOSURES ON STANDARD PROFILE (Table 1 Profile)

DATE	DIVE NO*	P_{O_2} bar	SYMPTOMS
Oct 73	54	0.4	1 diver: knee injury on bottom, right knee niggle on surfacing. 1 diver: right knee pain incidents at 120 m. 1 diver: knee niggle 23 min after arriving at 100 m, still tender at 85 m.
Nov 73	55	0.4	None.
Jan 74	56	0.4	3 divers: "something moving in knee" on arrival at 5 m and on surfacing.
Feb 74	57	0.22 on bottom 0.4 decompression	None.
Feb 74	58	0.22 on bottom 0.4 decompression	2 divers: mild aches in knees postdive. 1 diver: slight pain left knee at 115 m, 2¼ hours into stop.
June 74	59	0.22 on bottom 0.4 decompression	1 diver: niggle on surfacing.
July 74	60†	0.4	None.
July 74	61	0.4	None.
Sept 74	64	0.4	None.
Oct 74	65	0.22 on bottom 0.4 decompression	1 diver: transient aching in anterior thighs during drops to 5 m and surface.
Nov 74	66††	0.4	None.
Nov 74	67††	0.4	2 divers: transient knee and thigh stiffness on all drops between 15 m and surface. First began at 160 m, reported 20 m.

* Three subjects per experiment; total of 23 individual man-dives.
† including 6 x 1-nour excursions to 300 m.
†† including 3 x 1-hour excursions to 300 m.

TABLE 3 - FURTHER TRIALS OF STANDARD '250 m' PROFILE

DATE	DIVE NO*	DEPTH (m)	SYMPTOMS
May 76	4	200	Diver PA: Bilateral knee pain on all drops 15 m to surface.
Sept 76	5	300	Diver MT: Left knee pain on drop from 25 m, both knees all drops 15 m to surface. Pain settled within 5 minutes of arrival at new stage.
Feb 77	6	300	Diver PA: Left knee pain on 10 m drop, clearing after 10 minutes; fairly severe same knee on 5 m drop.
May 78	77†	200	Both divers: Niggles on all drops from 20 m, 5 m drop very painful.
Nov 78	81	300	1 diver: Left shoulder niggle 20 m, 5 minutes O_2 therapy, 5 minutes before and after each move thereafter. 1 diver: Treated for delayed action niggle bend left knee, 23 hours after surfacing. 1 diver: Dull ache right knee from 70 m, not reported.
Oct 79	10B	180	1 diver: Transient right knee and thigh niggle on 45 and 40 m drops. Duration of all subsequent drops (from 35 m) slowed from 5 to 30 minutes.

*Dry Chamber Series, 2 subjects per experiment, except DTU Dives 77/81 - 3 subjec

†Decompression commenced with an upward excursion to 159 m (as permitted by the USN Diving Manual).

Nevertheless, it was obviously desirable to continue to use the 250 m table as a basis for comparison, and thus the issue resolved into that of designing a path from 420 m to 250 m, where the standard table would be commenced.

DIVE 7 PROFILE

It was agreed to use 5 m stages throughout the ascent. The path between 420 m and 300 m was broken down into 7 drops/2-hour stages, per day, with a 12-hour hold overnight. (Effective average rate approximately 1.4 m/hour or 35 m/day; the average daily rate depends on which particular 24-hour period is chosen.)

As noted above it was assumed that this rate may be too fast to allow 250 m to be reached directly and a precautionary and experimentally convenient 33-hour hold was inserted at 300 m. Between 300 and 250 m a similar average rate was maintained using 4-hour stages without overnight holds. Thereafter the standard 250 m profile was followed. The profile, shown in the Appendix at the end of the report, was carried out in October 1977.

These rather ad hoc measures were successful in getting the divers to 55 m. On the 50 m drop, subject PA reported slight twinges in both knees. The Duty MO ordered all subsequent 5 m drops to take 25 instead of 5 minutes. The 40 and 35 m drops produced further twinges in the right knee, and both knees ached on the last $\frac{1}{2}$ m of the 10 m drop. Pure oxygen on BIBS was used on the last 5 m drop to the surface, with a recurrence of left knee pain at 0.4 m. The decompression was actually halted for a few minutes during this final drop when bubbles were heard ultrasonically.

In analysing this decompression, it was clear that the standard decompression schedule could not be extrapolated beyond 250 m. If the 33-hour hold at 300 m was adequate to re-equilibrate at this depth, then either the more conservative 4-hour stages between 300 and 420 m were inadequate (when compared to the initial 3-hour stages of the standard 250 m profile) or some other factor was implicated. One possibility was that the final 6 or 7-hour stages were simply too short. However, the average rates represented by these stages are very slow, 0.83 and 0.71 m/hour respectively (2.7 and 2.3 ft/hour), when compared with USN and other saturation decompression rates.

A much more realistic hypothesis was that the 5 m drops were too large. Thus, while average rates remain conservative, the instantaneous rates of 1 m/minute over a 5 m drop were too large. In particular it should be recalled that the P_{O_2} was 0.4 bar (4 m) on all these profiles, and it is possible that any drop in excess of the 'inherent oxygen window' was potentially provocative over a long

decompression. If these 5 m drops could initiate a gas phase, then it could well be forming quite early on in the decompression. Clearly then the rest of the profile could be viewed as a partly successful therapy, although the effects of a stabilised gas phase in the joints could not be considered very desirable (subject PA carried a gas phase in the knees from 50 m to the surface - a total of 64 hours). With this background, it appeared that a new approach was required to deep saturation decompression profiles.

DESIGN OF THE DIVE 8 PROFILE TO 420 m

The decompression profile of the present series was not the subject of a specific research project, and any decompression experiments had to be designed against a set of limiting constraints (see later).

The primary aim in designing the new profile was to remove some of the provocative aspects of the standard 250 m profile and its extrapolations, while allowing room to vary decompression parameters in the succeeding series of experiments.

The Ideal Profile

The first stage was to design the ideal profile and then fit it to the set of constraints. The following assumptions guided the theoretical design:

1. The slowest tissues control the rate of ascent on a saturation dive, insofar as if a state of supersaturation is maintained, there is a risk of a gas phase developing, which will, in due course, lead to decompression sickness. The ideal/safe saturation profile should avoid the formation of a gas phase at all stages of the ascent. (On short duration shallow saturation profiles it may be possible to get away with a gas phase over the final stages of the ascent, but this would certainly be undesirable from deeper saturation levels.)

2. Ordinary dissolved gas elimination from the slowest tissues may be modelled by a set of linear compartmental differential equations (Model A). If a gas phase forms, the biophysics of inert gas exchange will alter and the model must be replaced by one or more non-linear equations (Model B).

Model A

In the ideal case a gas phase will have been avoided on the ascent, and Model A can be used to predict the ascent rate. The tissue response (see Appendix) was derived for nitrogen elimination, directly from the standard air no-stop dive curve. This was then corrected for helium, by increasing the time constants by a factor of 3. However, authentic no-stop oxy-helium data to test this corrected response curve does not exist (the standard

no-stop oxy-helium table is contaminated with 0.8 bar tissue nitrogen and post-dive air on the surface). In the case of a saturation profile on P_{O_2} = 0.4 bar, balance helium, the model predicted that the ascent rate should be at a constant continuous rate of 4 m/hour (96 m/day), but in view of the above uncertainty, this figure had to be treated with caution. Nevertheless, the Comex Sagittaire IV 610 m (2001 ft) profile of 1974 successfully employed similar rates over a large range of the deep portion of the ascent (typically 5 m/hour falling to 4 m/hour between 610 and 400 m at a P_{O_2} of 0.5 bar)(4). Again, on the PL 457 m (1500 ft) dive of 1970(5), on the second attempt to ascend (after a vestibular bend had occurred at 390 m at a rate of 13 m/hour), a continuous run from 457 m to 91 m (300 ft) was carried out at a rate of 3 m/hour on a P_{O_2} = 0.45 bar. This ascent actually began with a rapid upward pull from 467 m (depth of recompression) to 457 m. Model B (described below) predicted a knee pain onset depth of 268 m, and niggles were first noted in both subjects at 265 m and again at 222 m, but not severe enough to halt the ascent. It could have been argued that the 3 m/hour rate was not too fast and that these niggles were really caused by the initial one bar rapid drop or were a left-over from the first (abortive) ascent from 457 m (1500 ft)). In any event, at the time of planning the Dive 8 profile it could not have been positively asserted that a continuous rate of 3-4 m/hour was inherently provocative at a P_{O_2} of 0.4 bar.

Model B

An attempt was made to develop an approximate model to predict the case of a gas phase leading to mild limb bends, on various saturation profiles carried out in the DTU from 1969-1974(6). It was assumed that a gas phase occurred early on in the ascent, and grew through the interaction of pressure reduction and inter-tissue diffusion. A simple non-linear model was proposed and its unknown numerical parameters were evaluated using the results of Dives 18 and 19 in the early DTU dive series(1). Furthermore, it was found that this calibrated model predicted in turn the onset depth of decompression sickness occurring on other saturation profiles in the UK and USA to a good order of accuracy. The model predicted that such a gas phase would disappear, if the ascent rate did not exceed a constant rate of 1.17 m/hour (28 m/day) on a P_{O_2} of 0.4 bar. Just as the calculation of Model A seemed to be in general agreement with that of the Comex 2001 ft and PL 1500 ft dives so the Model B prediction was equally close to that of the USN daily rate of 29.3 m (96 ft) per day! The dilemma

of which rate to try out was removed by the following constraints and precautions:

a. The profile should be as conservative as possible, bearing in mind that this was not a formal part of the experiment. This eliminated the 4 m/hour continuous rate.

b. A nightly hold of 8-10 hours was required to avoid the possibility of decompression sickness arising overnight, while on the move. The theoretical continuous rates of either 1.17 m/hour or 4 m/hour were thus impossible to carry out in this case.

c. A daily hold of 4 hours was required to carry out various experiments where a falling pressure would be undesirable. This left only 12 hours or less of the day for decompression.

FINAL DESIGN AND RESULTS OF DIVE 8

After a careful assessment of practical and theoretical aspects, it was decided to follow a 'linear' profile at a daily average rate of 28 m/day, but to accelerate the actual hourly rate to 4 m/hour (spread over 7 hours running time per day). This compromise appeared to provide adequate safety whilst offering a rationale by which future decompression experiments could be designed. It was not certain whether the Model A 4 m/hour rate could itself provoke a gas phase if maintained for a sufficient number of hours during each day, and as a safeguard the Model B daily average of 28 m would allow any resulting accumulated gas to disappear. If the profile failed, it would not be immediately possible to identify whether the daily or hourly rate had been too fast, but by holding the 28 m/day constant and varying the hourly rate over a series of trials, it should be possible to deduce the correct rate(s). In any event the planned profile was actually slower than the extrapolated 250 m standard profile at all levels deeper than 30-40 m, where the two curves crossed over (the precise crossover point depends on the time of day that the ascent begins).

As an additional safety precaution the medical cover officer requested that this final 30 m be carried out using the standard profile (as in Table 1), but with the 5 m drops at 4 m/hour. A typical day of the ascent is shown in Fig 1. Dive 8 was carried out in February 1978, and the results (together with 5 following trials) are given in Table 4.

The decompression proved to be completely successful, and the post-dive platelet count was steady, suggesting that unlike earlier dives a gas phase had been avoided. Subject DH referred to the ascent as a 'wonder decompression', in comparison with the extrapolated 'standard' profile which he had carried out in Dive 6 from 300 m with accompanying bouts of niggles towards the surface!

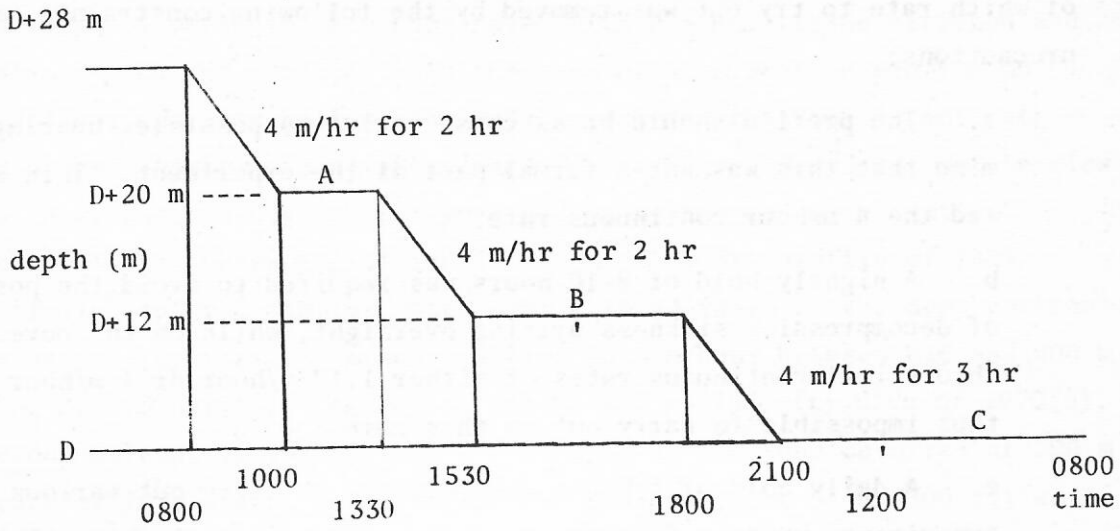


FIG 1 - Typical Day (at 28 m/day rate)

FURTHER EXPERIMENTS

The next logical step following Dive 8 was to carry out a 28 m/day ascent as far as possible all the way to the surface.

The first opportunity to test this procedure occurred in March 1979 on Dive 9A, a 180 m 'training dive' for subjects DM and DE. The first day began with a preliminary 2 m drop at 4 m/hour, with a 28 m/day ascent thereafter, following the format in Fig 1. The final day from 10 m to the surface was carried out at 1 m/hour. This slightly slower rate than the theoretical value of 1.17 m/hour was introduced to form a cautious transition from the previous terminal stages of the Dive 8 profile, and to allow for the falling P_{O_2} from 6 m (where the O_2 reached a value of 25% by volume, dropping from 0.4 bar to 0.2 bar at the surface). The ascent was most successful and provided the encouragement for the next experiment.

This occurred on DTU Dive 87 in May 1979 to 200 m. The first day began by decompressing 12 m at 4 m/hour from 200 to 188 m. Over the next 6 days 28 m/day was carried out following the scheme in Fig 1. The final 20 m, on the eighth day, followed as far as possible Fig 1 (instead of modifying the final 6-10 m). Subjects NAD, CD and BD successfully completed the profile totalling 169 hours actual duration (the theoretical continuous ascent of 1.17 m/hour should have taken 171.43 hours). The standard profile of Table 1 would have required 186 hours, ie 10% longer. This result was encouraging as it suggested that the final stages could be taken at the 4 m/hour rate, providing a gas phase had not formed, and that at least 20 m could be covered on the final day at this rate.

TABLE 4 - TRIALS OF THE 28 m/DAY EXPERIMENTAL PROFILE†

DATE	DIVE NO*	DEPTH (m)	HOURLY RATE (m/hr)	FINAL DAY/ STAGES	SYMPTOMS
Feb 78	8	420	4	Standard Table 1 profile from 30 m with drops at 4 m/hr	None
Mar 79	9A	180	4	1 m/hr from 10 m	None
May 79	87	200	4	Final 20 m following Fig 1 format	None
May 79	9B	540	4	(USN Sat Profile from 38 m)	Both divers - knee pain/niggles 38 m
Sept 79	10A	180	1.75	1.75 m/hr from 19 m	1 diver - right mid-thigh niggle at 12 m and 2 hr after surfacing. Recurrence of left mid-thigh pain on recompression (unreported pain at 90 m, which had 'cleared')
Feb 80	11	300/180††	4	1.17 m/hr from 30-10 m and 10 m to surface on final day	None

* Dry Chamber Series, 2 subjects per experiment, except DTU Dive 87 - 3 subjects.

† Following format of Fig 1 over main part of ascent, except Dive 10A.

†† Ascent from 300 m, but 41-hr hold inserted at 180 m.

Following on the results of these two dives, the schedule for Dive 9B to 540 m in May 1979 was planned along similar lines. As usual the P_{O_2} was set at 0.4 bar, and 26 m was decompressed on the first day, with 28 m/day thereafter; again, following the format of Fig 1. The intention was to arrive at 10 m (on the penultimate day) and complete the final 10 m at 1 m/hour the next day (following Dive 9A rather than Dive 87, in view of the greater saturation depth). However, at approximately 38 m, towards the end of that day's 28 m run, both divers, PM and DW, complained of knee pain/niggles, and a cycle of oxygen breathing was initiated. The ascent was successfully completed (following an overnight hold) from 38 m according to the conservative USN standard saturation profile. This result indicated that the 4 m/hour rate may well be too fast, particularly towards the final stages of a long ascent, and that there did not appear to be a strong argument to suggest that the 28 m/day average rate was itself too fast, in view of the aforementioned uncertainty in Model A which lead to the prediction of the 4 m/hour rate continuous rate.

Accordingly, on Dive 10A to 180 m (originally planned to 540 m) in September 1979, with subjects DM and RMcK, the hourly rate was cut back to 1.75 m/hour, spread over 16 hours/day, giving the same average of 28 m/day. This rate was very similar to that of the USN - 6 ft(1.82 m)/hour over 16 hours or 96 ft(29.3 m)/day - and no problems were expected, particularly from such a shallow depth of 180 m. However, this profile also failed, but in a rather unexpected way. First of all when the target depth of 540 m was suddenly altered to 180 m, during the compression phase a new schedule had to be prepared at short notice and a small error was made in designing the stages of the new schedule. Thus, instead of planning to arrive at 10 m on the penultimate day, a depth of 19 m was to be reached, and carried out on the final day at 1.75 m/hour. (Even though 20 m had been successfully covered on the final day of Dive 87 at 4 m/hour, it was felt that 10 m was the safer figure.) Furthermore, due to a simple arithmetic error in calculating the correct depth to decompress on the first day, the dive surfaced about 3½ hours sooner than the theoretical continuous rate.

At first it was thought that these deviations contributed to the resulting bend in one subject: on the final day at 12 m, DM reported right leg niggles, mid-thigh, which recurred 2 hours after surfacing, worsening. He was recompressed to 18 m on O_2, with pain now "returning" in the <u>left</u> (hitherto unreported) mid-thigh, and now worse than the right leg. He obtained relief at 9 m. It later transpired that the "returning" pain in the left leg had first occurred at 90 m(!), which had not been reported to the MO at the time although the subject had noted the event on the psychological form the next day after leaving 90 m. The interpretation of this profile was complicated by the fact that (a) the

greater part of the ascent was virtually a USN schedule, (b) a deviation had been made in the final stages of the schedule design, and (c) the very deep (90 m) depth of an event which by hindsight appeared to be decompression-related. Nevertheless, the next 180 m 'training' dive (10B) in October 1979 saw a return to the old standard 250 m schedule of Table 1 (which too led to decompression difficulties, as detailed in Table 3!).

With this conflicting evidence, one was forced to fall back on the original assessment of the standard profile, viz that 5 m drops on a P_{O_2} of 4 m, were undesirable, and a return was made on Dive 11 to the general strategy of the previous paragraphs. This was a 300 m (originally 540 m) exposure, again with P_{O_2} = 0.4, with subjects ME and MR, carried out in January/February 1980.

The ascent followed the profile in Fig 1, but a 41-hour hold was inserted at 180 m to carry out experiments. This period may be thought of as an effective resaturation at 180 m, and thus only the decompression from 180 m is of interest.

The first day of the ascent from 180 m was carried out at the theoretical rate of 1.17 m/hour to 170 m. Thereafter 28 m/day average was completed following the scheme in Fig 1, until a depth of 30 m was reached. On the penultimate day the ascent was continued from 30 to 10 m at 1.17 m/hour, with the final 10 m being completed the next day, at the same rate. These slow rates over the final two days were inserted in view of the peculiar events on Dive 10A. The decompression was completely successful.

CONCLUSIONS

It is clear that the standard 250 m table cannot properly be extended to 300 m without modification to the rest of the profile. The 40 m/day average rate over the deep portion is too fast, and/or the 5 m drops are too large on a P_{O_2} of 0.4 bar (4 m). The linear/night hold profile introduced on Dive 8 in February 1978 has proved to be popular among chamber crew and divers alike, but more research is needed to clarify the tolerances of the daily (average) rate and hourly rate. At the present time there does not appear to be any reason to alter the 28 m/day rate (on a P_{O_2} of 0.4 bar), but that the above hourly rate should not exceed 2 m/hour, a result very similar to the standard USN profile.

If this interpretation is correct, then the calculation for helium elimination, derived from the nitrogen Model A, is incorrect. What is really required is a high quality no-stop oxy-helium curve to enable the correct partition coefficients and diffusion/perfusion timescale dominance to be identified.

APPENDIX - CALCULATION OF ASCENT RATES

Model A. Gas Free Ascent Rate

From assumption 2, the average inert gas tension p (t) in the slowest tissue in response to an arterial tension $P_A(t)$ will be given by the following standard convolution integral

$$p(t) = p_o + \int_o^t (P_A(x) - p_o)\,\phi'(t-x)\,dx, \qquad \ldots\ldots\ldots\ldots (1)$$

where $\phi(x)$ is the 'transfer' function with $\phi'(x) = \frac{d\phi}{dx}$, and p_o is the initial equilibrium tissue tension.

In a saturation decompression, where the inspired PO_2 is kept constant,

$$p_A(t) = P_{AMB}(t) - PO_2, \qquad \ldots\ldots\ldots\ldots (2)$$

and

$$p_o = P_{SAT} - PO_2, \qquad \ldots\ldots\ldots\ldots (3)$$

where $P_{AMB}(t)$ is the ambient absolute pressure (bar)

and P_{SAT} is the bottom saturation pressure.

On a continuous linear ascent, at a rate α (m/hour), ambient pressure at any time t (hr) is given by

$$P_{AMB}(t) = P_{SAT} - \frac{\alpha t}{10}. \qquad \ldots\ldots\ldots\ldots (4)$$

The average tension p (t) can be solved from these four equations (given ϕ (t)). However, what is not known is the criterion for avoidance of free gas in this tissue. The simplest hypothesis is to assume that no free gas will be liberated providing p (t) does not exceed ambient pressure $P_{AMB}(t)$ by a small (positive) constant, say k.

The justification for the latter criterion is as follows. Obviously, a tissue can remain in a state of supersaturation for quite large times. Why then should a profile be designed for the restrictive condition of avoidance of super-saturation (above a value k)? The underlying hypothesis discussed in (6) (and again in Model B below) is that any excess tension will be relieved by very small arterial bubbles invading the tissue. These bubbles probably originate as cavitation nuclei in the right side of the heart, which obviously carries the entire fast tissue (and the most supersaturated) inert gas load on ascent! These nuclei grow rapidly in the pulmonary artery, pass into the lung, where they are partially filtered to emerge after an appropriate time delay in the arterial system as very small finely-graded bubbles. These bubbles, rapidly

collapsing in the now undersaturated blood, invade the whole body randomly. Only those tissues which carry an excess of inert gas with respect to that of the 'interogating' arterial bubble will have an opportunity to succeed in bubble 'capture'. The time delay through the lungs (of the order of a few minutes) will allow certain fast tissues such as the CNS to offload their excess gas thereby sustaining on invasion of small and collapsing bubbles. The time delay will be reduced in a rapid decompression with consequent involvement of very fast tissues such as the heart, brain, spinal cord, etc. (In an extremely rapid ascent, such as in submarine escape, the time delay is probably only seconds, rather than minutes.)

Accordingly, for a single inert gas, the safe ascent criterion for the tissue in question is taken to be

$$p\ (t) \leq P_{AMB} + k \qquad \ldots\ldots\ldots\ldots\ (5)$$

where k is a small permitted excess (to allow for CO_2, 0_2, H_20 and surface tension) = .25 bar (7).

The transfer function $\phi\ (t)$ is assumed to have the triple exponential form

$$\phi\ (t) = 1 - A_1\, \bar{e}^{\,k_1 t} - A_2\, \bar{e}^{\,k_2 t} - A_3\, \bar{e}^{\,k_3 t} \qquad \ldots\ldots\ldots\ldots\ (6)$$

where $A_1 + A_2 + A_3 = 1$ ie $\phi\ (0) = 0$ and $\phi\ (\infty) = 1$.

Substituting (2), (3) and (6) into Equation (1) and applying the criterion (5), we obtain an integral equation for the ascent profile, $P_{AMB}(t)$:

$$P_{AMB}(t) = P_{SAT} - (P_{O_2} + k) + \int_o^t (P_{AMB}(x) - P_{SAT})\ \phi'\ (t-x)\ dx,$$

This equation is easily solved by Laplace Transforming both sides.

Thus, defining the Laplace Transform of f (x) as $\bar{f}\ (s) = \int_o^\infty \bar{e}^{\,sx}\ f\ (x)\ dx$, the transform of the equation is

$$\bar{P}_{AMB} = \frac{P_{SAT}}{s} - \frac{(P_{O_2} + k)}{s} + \left[P_{AMB}(s) - \frac{P_{SAT}}{s}\right] s\ \phi'\ (s),$$

which may be solved for $\bar{P}_{AMB}(s)$ to give

$$\bar{P}_{AMB}(s) = \frac{P_{SAT}}{s} - \frac{(P_{O_2} + k)}{s^2} \quad \frac{1}{\left[\frac{A_1}{s + k_1} + \frac{A_2}{s + k_2} + \frac{A_3}{s + k_3}\right]} \qquad \ldots\ldots\ldots\ldots\ (7)$$

It can be shown by inversion of (7) that on a long deep decompression the transient components of $P_{AMB}(t)$ will die out. In other words, the slowest rate of ascent will be achieved at large (asymptotic) times, and this solution of (7) is obtained very simply by letting $s \to o$ and inverting the result, to obtain:

$$P_{AMB}(t) \sim P_{SAT} - \frac{(P_{O_2} + k)\, t}{(A_1/k_1 + A_2/k_2 + A_3/k_3)} .$$

Thus the ascent rate is effectively linear at large times, with a rate given by

$$R = \frac{(P_{O_2} + k)}{(A_1/k_1 + A_2/k_2 + A_3/k_3)} . \qquad \ldots\ldots\ldots\ldots (8)$$

If the profile is linear throughout, as in (4), the rate should not exceed the value predicted by R in Equation (8).

The values of A_1, A_2, A_3 and k_1, k_2, k_3 were derived from an analysis of the RN and USN Standard air no-stop curve. Each curve was fitted to the formula

$$D\, \phi_{N_2}(T) = D_\infty$$

where D is the depth of the dive for a time T, and D_∞ the indefinite dive threshold depth. A value of $D_\infty = 7m$[7] was chosen to find a least squares fit of a special subset of the RN curve. The result (below) led to an excellent fit:

$$A_1 = .7546, \quad A_2 = .1662, \quad A_3 = .0792,$$

$$k_1 = .004196\ \text{min}^{-1}, \quad k_2 = .03821\ \text{min}^{-1}, \quad k_3 = .6675\ \text{min}^{-1}.$$

Thus for nitrogen the ascent rate should not exceed $R \leq 10 \times \frac{(.4 + k)}{3.0718}$ m/hour; k is usually chosen = .25[7], but to err on the safe side, it is set to zero with the result $R_{N_2} \leq 1.3$ m/hour (or 46 minutes/m).

For helium, an accurate no-stop curve is not available and it is not known how each nitrogen value for A_1, A_2, A_3 and k_1, k_2, k_3 must be adjusted to yield a prediction for the helium transfer function $\phi_{H_e}(t)$. A simple conversion can be made by assuming that the tissue is predominantly either lipid or diffusion limited. It can be shown that this conveniently allows all the time constants k_1, k_2, k_3 to be increased by a factor of about 2.65 - 3 (the oil water partition coefficient or Grahams law correction as the case may be). (If the actual situation is an interaction between perfusion, diffusion and fat/water ratios, no such simple conversion will be possible.)

The ascent rate on helium is therefore increased to a value between 2.65 and 3.0 times that of the nitrogen rate,

ie R_{H_e} = 3.4 to 3.9 m/hour.

In view of the uncertainty of this N_2-He conversion, the theoretical ascent rate chosen for experimental evaluation was 4 m/hour.

Model B. Ascent Rate with a Gas Phase

This model has been previously described in (6) and is summarized here.

When a gas phase appears the biophysics of elimination will change, and Model A is no longer valid. The rate of elimination of both free and dissolved gas in such a zone will now be very much slower: blood perfusion will be reduced through distortion or occlusion of capillaries by the expanding gas, which can only be eliminated by the much slower process of inter-tissue diffusion to more well-perfused zones.

In examining the cause of a bend incident, it would not be clear whether the mathematical model of inert gas elimination or the criterion used to avoid the formation of free gas was incorrect.

This difficulty is compounded by the general belief that if a gas phase does form, then it probably occurs much later in the decompression, nearer the surface, where the incidence of decompression sickness is highest.

This is an example of 'linear thinking', viz that a response (incidence of decompression sickness) is assumed to be proportional to the stimulus (pressure reduction ratio). It makes no allowance for duration of application of the stimulus, an effect which may well only become noticeable towards the end of a long ascent.

In other words, it is possible that a gas phase forms shortly after beginning the ascent, but only becomes manifest much later in the decompression.

If this is correct then on the early (unsuccessful) profiles, it is the initial stages that are at fault rather than the final stages. This is supported to a large extent by the fact that nearly all these profiles from saturation began with a rapid drop of between 5 and 10 m, 'to set up a gradient' to accelerate the elimination of inert gas.

It is assumed that simple bends pain is caused by a disturbance of a nerve ending through the presence of a nearby distribution of expanding gas, which has reached some critical volume per unit volume of tissue. The source of this free gas is a matter for conjecture, but as described in Model A, it is assumed that small bubbles arrive on the arterial side of a tissue and fail to traverse it because the nett positive influx of gas molecules into the bubble is sufficiently large to 'capture' it within its residence time in the capillary.

A final point favouring arterial bubbles is that they form a convenient method of rapidly bringing a supersaturated tissue into equilibrium (where all excess gas is

'dumped' before it has a chance to be vented via circulation). A quick release mechanism of excess gas is needed to explain the rapid onset of symptoms in 'max pull' threshold exposures.

Note, on the other hand, that a supersaturated tissue may not always be able to capture a bubble at great ambient pressures even if the residence time is normally long enough at lower pressures. This is because the rate of change of bubble radius is inversely proportional to the ambient pressure (and proportional to the tissue-bubble inert gas gradient). Thus the 'zero' supersaturation safe ascent criterion Equation (5) of Model A may be unrealistically restrictive for very deep exposures and may offer an alternative explanation for the remarkably rapid ascents achieved on the Comex and Atlantis series.

If an arterial bubble is captured by the tissue, it will most likely lodge toward the venous end where the tissue-bubble gradient will be largest. Some gas evidently leaks back into the venous return to form venous gas emboli, but essentially the tissue will be locked off by capillary occlusion. Gas will probably 'track' back up the capillaries, thereby providing a convenient mechanism for dumping all excess gas and preventing its escape. It is supposed that this zone soon stabilizes into a tissue-bubble matrix, devoid of circulation, except at its periphery, where a fast well-perfused tissue must exist (for otherwise it too would contain free gas).

The model as envisaged is too complex and a number of first order approximations must be made. The first is that the volume of released gas per unit volume of tissue v(t) is assumed to be spatially uniform and dependent only on time. The second is that the total surface area of free gas is effectively constant.

Whilst the first assumption is a reasonable simplication, the second needs some justification. If indeed gas is distributed throughout long sections of the capillaries, its surface tension will be small and effective radius large. The nearest comparable physical situation might be that of, for example, microbubbles occurring naturally in sea water. Those with a radius r over 60μ appear to be distributed with a number density proportional to $\frac{1}{r^2}$(8). This means that the total surface area is effectively constant for such large bubbles of low surface tension, and this is taken to be a reasonable approximation for long tubular bubbles in tissue.

The differential equation may now be simplified to a statement that the rate of change of gas in the critical tissue is proportional to the inert gas gradient between the equilibrated zone and that in the peripheral circulation. Thus

$$\frac{d}{dt}\left[(s + v(t))\ (P_{AMB}(t) + k)\right] = -\beta s\ (P_{AMB}(t) + k - P_A(t)), \quad \ldots\ldots\ldots (9)$$

where $v(t)$ = volume of free gas/unit volume of tissue

$P_{AMB}(t)$ = ambient pressure

$P_{AMB}+k$ = partial pressure of inert gas in equilibrated zone

$P_A(t)$ = arterial pressure of inert gas

s = solubility of inert gas in the critical tissue

β = constant equal to the product of surface area and diffusion coefficient per unit length of diffusion distance

k = small correction to allow for tissue elasticity, blood pressure, presence of O_2, CO_2, H_2O and surface tension.

Equation (9) may be simplified, using Equation (2), to:

$$\frac{d}{dt}\left[(1 + \frac{v(t)}{s})\quad (P_{AMB}(t) + k)\right] = -\beta\ (P_{O_2} + k). \quad \ldots\ldots\ldots (10)$$

This equation may be integrated to yield

$$1 + \frac{v(t)}{s} = \frac{(1 + \frac{v_o}{s})\ (P_{SAT} + k)\ -\beta(P_{O_2} + k)\ t}{P_{AMB}(t) + k}, \quad \ldots\ldots\ldots (11)$$

where v_o is the initial distribution of free gas (if any) at the saturation pressure P_{SAT}.

Thus the volume of gas per unit volume of tissue is a non-linear function of time, unless the ambient pressure is constant. Further, it can be seen that collapse time for the gas at a fixed pressure P_{AMB} is a linear function of the ambient pressure for equal volumes, viz

$$T_{COLLAPSE} = a(P_{AMB} + k).$$

Thus the time for a given volume of gas to redisolve is approximately proportional to the ambient pressure (since k is small). This rather obvious qualitative fact has tended to be overlooked when treating deep cases of decompression sickness - proportionately much longer periods must be allowed for dissipation of equal volumes of gas at greater pressure.

Note that if there is no initial distribution of free gas (ie $v_o = o$), then the term $(1 + \frac{v_o}{s})\ (P_{SAT} + k)$ on the right hand side of Equation (11) must be replaced by $P_{SAT}-P_{O_2}$, since this is the actual inert gas tissue tension in the absence of a gas phase, at the start of the ascent.

$$\text{Thus } 1 + \frac{v(t)}{s} = \frac{P_{SAT} - P_{O_2} - \beta(P_{O_2} + k)\, t}{P_{AMB} + k} \quad \ldots\ldots\ldots\ldots (12)$$

Equation (12) is used for a direct decompression from saturation which provokes a gas phase early on in the ascent.

Application to Saturation Data

Equation (12) contains two unknown parameters β and k, and the threshold value $v = v_c$. The dependence of β can temporarily be eliminated by considering the case of rapid decompression from saturation to the threshold depth, just short of provoking a mild limb bend. It is assumed that a gas phase forms, reaching the critical value v_c with very little dissipation in a rapid ascent. Thus setting $t = o$ and $v = v_c$ in Equation (12), it is seen that the exposure pressure P_{SAT} and decompression pressure P_{AMB} are linearly related, with a slope of $1 + \frac{v_c}{s}$, and an intercept dependent linearly on k.

The value of these two 'steady state' parameters was established as 1.397 and 2.5 m respectively by Hennessy and Hempleman (7) in their analysis of the 'big drop long stop' saturation experiments reported by Barnard (1).

The unknown parameter β was determined by calibrating the model against two particular dives of the above series where a critical volume of gas was reached after one drop, and again, after a long stop, on a second drop of the same experiment. It had been shown on earlier dives of that series that it was just possible to carry out a threshold decompression from 69 m to 47 m and thence to 24 m to 10 m to the surface, spending 24 hours at each level, breathing .22 bar O_2, balance helium. On Dive 18, the 24 hour period at 24 m was shortened to 18 hours, and one diver complained of slight aches on arrival at the 10 m level. Similarly, on Dive 19, the 47 m level was shortened to 18 hours, resulting in one diver experiencing pain in both knees on the drop to 10 m. It is not clear at which depth pain commenced but relief was felt on recompression to 20 m. These valuable experiments provide two estimates of β. In the first case, it is assumed that a critical volume of gas is first achieved at 24 m and again 18 hours later at 10 m, and application of Equation (11) yields a value of $\beta = 3.9 \times 10^{-3}$ min^{-1}. In the second case, the critical volume first occurs at 47 m and again 42 hours later at 20 m, resulting in a value of $\beta = 3.2 \times 10^{-3}$ min^{-1}. Erring on the side of safety, a value of $\beta = 3.0 \times 10^{-3}$ min^{-1} was chosen for the model.

Equation (12) with $v_c/s = .397$, k = 2.5 m and $\beta = 3.0 \times 10^{-3}$ min^{-1} may now be used to correlate simple limb bends on well-known decompressions. Table 5 shows the results of 3 experiments carried out at the Physiological Laboratory, Alverstoke in 1970 (5).

The profiles all began with a rapid drop of 9 m, followed by a mono-exponential curve, with the exception of the linear profile from 457 m. (The latter curve was substituted, after an occurrence of eighth nerve disturbance (END) at 390 m on the exponential profile.) Predicted values are in very good agreement with knee niggle/pain onset depth, and all are on the safe side.

A representative sample of various ascents from saturation in the US is shown in Table 6 (9, 10). Again, the correlation is good, although there are 3 dives which should have produced decompression sickness, for complete consistency. Note that even though the decompression from 320 m in Predictive Studies IV did not contain an initial rapid upward ascent, the divers had previously carried out provocative excursions from 244 to 365 m and back (9).

The model has been adequately calibrated and checked to allow a prediction of the safe linear rate of the ideal decompression, viz that profile where a gas phase may have been provoked at the initial stages of a decompression, but the rate so chosen such that the volume of gas is just maintained at a zero level. By setting v = o in Equation (10), the ascent rate R is given by

$$R = \frac{d}{dt} P_{AMB}(t) = -\beta (P_{O_2} + k) . \qquad \ldots\ldots\ldots\ldots (13$$

Thus in the case of a decompression at a constant partial pressure of oxygen, the ideal rate of ascent is also constant. Table 7 has been prepared from Equation (13) (with k = .25 bar and $\beta = 3 \times 10^{-3}$ min^{-1}) and shows the ascent rates for various P_{O_2} values. Compare the m/hr rates with those of Tables 5 and 6. In particular, for P_{O_2} = .4 bar, Model B predicts an ascent rate of 28 m/day, the value chosen for experimental evaluation on the present deep dive series.

TABLE 5 - RN SATURATION EXPOSURES 1970 (Ref 5)

Exponential ($P=P_{SAT}e^{-kt}$) Decompression, P_{O_2}, .45 Bar.

Depth (m)	Rate Const (k) (h^{-1})	Initial Ascent Rate (m/hr)	Result Knee-Pain Onset Depth (m)	Prediction (Eqn 12) (m)
91	0.052	5.25	38	56
137	0.040	5.88	83 - 86	86
(457)	(0.028)	13.08	(390 END)	-
457	-	3.00 (linear)	265	268

END: Eighth Nerve Disturbance.

Initial Drop 9 m in all cases.

TABLE 6 - US HELIUM SATURATION EXPOSURES. LINEAR DECOMPRESSION.

Source	Depth (m)	P_{O_2} Bar	Initial Drop (m)	Ascent Rate (m/hr)	Result Knee-Pain Onset Depth (m)	Prediction (Eqn 12) (m)
USN GENESIS (E), 1963	61	0.5	10	2.22	OK	22
USN EDU, 1963	91	0.5	10	2.22	23	37
(Therapy)			-	1.11	OK	OK
USN EDU, 1964	91	0.5	10	1.66	OK	22
USN EDU, 1964	122	0.5	10	1.66	OK	32
LINK-UNIV Pa, 1964	130	0.5	9	1.52	7	20
USN SEALAB II, 1965	62	0.3	9	1.83	11	27
USN SEALAB III,	137	0.3	9	1.46	?	24
(Therapy)			-	1.04 overall	OK	OK
EDU/DUKE UNIV, 1968	305	0.3	9	1.07 overall	46	46
PREDICTIVE STUDIES IV, 1975	320	0.5	-	1.92 overall	152	163

TABLE 7 - LINEAR ASCENT RATE FOR GAS-FREE DECOMPRESSION

P_{O_2} Bar	m/h	m/day
.22	.85	20
.30	.99	24
.40	1.17	28
.50	1.35	32
.60	1.53	37

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