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Observations on no-stop and repetitive air and oxynitrogen diving

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Leitch DR, Barnard EEP. Observations on no-stop and repetitive air and oxynitrogen diving. Undersea Biomed Res 1982; 9(2):113–129—The historical origins of the respective air decompression schedules of the British and United States Navies are reviewed with particular reference to the repetitive diving rules. No-stop diving is also discussed. A series of single dive and repetitive dive trials of the Royal Navy Air Table is presented. U.S. Navy and Royal Naval Physiological Laboratory (RNPL) 1968 repetitive dive rules were also tested according to their respective tables on a selection of dives. Comparison of the two methods produce a remarkably similar outcome for dives to similar depths. For dives to very dissimilar depths there is no comparison. The RNPL system has commendable simplicity but lacks the flexibility of the U.S. Navy system for use with successive dives to different depths. Observations on the results of a triple no-stop repetitive dive experiment are presented. It is concluded that little would be gained by further practical investigation of no-stop diving times.

air decompression
no-stop diving
repetitive diving

Despite the effort being invested in deep oxyhelium diving, the bulk of diving is, and is likely to remain, air diving to depths less than 200 ft (60 m). Whereas some divers continue to request longer dives with less decompression time, there is still a group that also requires more short dives within a given tidal period.

The literature and conference proceedings are swamped with theoretical papers on decompression. Much work is also published on animal decompression but only a little on working dive experience. Little has been published on work wherein the air tables in current use have been deliberately tested to the limit with repetitive dives. We consider that publication of some of the recent collective Royal Navy experience in testing some of these schedules may be of benefit to the theoreticians and to practical diving. This paper makes no attempt to discuss or to advance decompression theories; it simply reviews the history of the schedules in use and gives an account of their effectiveness in our hands.

There were some suspicions that the Royal Navy air schedules were not adequately safe at depths of 140 ft (42 m) and deeper for durations of 20 min or more. So before embarking on repetitive diving a series of dives to check the basic Royal Navy Air Table, Schedule 11, was performed.

With the advent of a new schedule, comprehensive testing would clearly not be possible. In Britain, generally, a small number of sections are given 10 or 20 dives, and if necessary the whole schedule is modified either empirically or by recalculation and then retested.

DEFINITIONS

To avoid confusion, the diving terms used in this paper are defined:

A *repetitive dive* is any dive that follows a previous dive within a certain time limit laid down in various decompression tables—e.g., two or more dives within 6 h according to the R.N. Diving Manual.

A *combined dive* is a second or subsequent dive whose decompression time is calculated by adding together the dive times of the preceding dive and the subsequent dive.

Dive time is the time that elapses between the diver's leaving the surface and leaving the bottom; it is this time that is used to calculate the decompression stops.

Descent time is the elapsed time from leaving the surface to arriving at the bottom.

Bottom time is the time that the diver actually spends on the bottom—i.e., dive time less the descent time.

Surface interval is the time between dives. Interpretation varies, but usually it is taken as the elapsed time between arriving at the surface and leaving the surface.

Decompression time is the elapsed time from leaving the bottom to arriving at the surface. In dives not requiring decompression stops it is known as *ascent time*.

No-stop dives are dives that are short enough to not require decompression stops.

REVIEW

As each generation of air decompression schedules has been developed a new set of repetitive diving rules has been applied. Therefore a review of the introduction of the relevant schedules is appropriate.

British schedules

The first stage decompression schedules were produced for the Royal Navy in 1907 (1) and were then widely adopted around the world. These Haldane schedules existed in two parts: the extensively tested Schedule I, which covered dives to as deep as 204 ft with decompression times only up to 33 min; and the barely tested exceptional dive schedule, Schedule II, from the same depths.

In providing for repetitive dives it was proposed that the dive times of all dives on the same day be combined and that this time be used to identify the stops required from the current dive. The shallower half of these stops was then used in combination with the deeper half of the stops for the current dive alone. If the stops did not divide evenly, then the greater part was used for the shallower part of the decompression. It was also suggested that increasing the surface interval would naturally make subsequent dives safer, so that the precautions might be halved after 1 h and disregarded after 2 h. These rules were adopted.

The results of trials of the deep air diving schedules for dives between 120 and 320 ft with oxygen decompression were published in 1933 (2). After a small increase in some of the oxygen stops (which probably resulted from experience), they went into routine use (3), although, until recently, their use was almost exclusively with a submersible decompression chamber.

If air decompression was used instead of oxygen, then the oxygen stops were multiplied by 2.5; this was Schedule III. Initially, repetition of these dives was not allowed in less than 36 h.

Schedules I and II continued in the Diving Manuals until 1943 (4), although the repetitive dive rules changed slightly: No Schedule II dives were allowed to be repeated within 12 h. Schedule I dives followed the basic Haldane repetitive dive rules for all surface intervals of less than 4 h. If the second dive was less than 33 ft (10 m) deep, then no precautions were required.

The repetitive dive rules of the 1956 Diving Manual (5) were changed to make the combined dive stops for the shallower half of the decompression period refer to the deeper of the two dives. Three repetitive dives were not permitted unless the third dive was shallower than 33 ft.

New schedules were issued in 1958 with the same format and guidelines as before. These were the result of Rashbass's (6) calculation based on Hempleman's (7) theories. They were empirically modified by Crocker (8) until they worked under test. The result was that Schedule I was shortened and had decompression times up to 35 min, and Schedule II was lengthened. Both schedules went as deep as 200 ft. Schedule I was so much shorter than the Haldane schedule that the repetitive dive rules were thought likely to be unsafe and so were abolished.

Because a set of schedules for repetitive dives was to be produced later, interim rules were issued (9). The broad restraints were unchanged, but no more than two dives were permitted on Schedule I within a 12-h period. The stops used were those for the combined dive time for the relevant dives, but at the deepest depth, and the total decompression was not to exceed 75 min. It was stated at the time that this was clearly giving longer decompressions than necessary. However, the proposed new repetitive dive system failed. It seems possible that testing repetitive dives of 140 ft for 25 min and of 180 ft for 20 min with intervals of 72–124 min may have only indicated the areas of weakness in the 1958 tables, which became more apparent later. A later and complex method, the Crocker "B" method (10), was devised but never tried.

The 1933 Schedule III appears to have been used only by specialists until it was issued in the Diving Manual of 1957 (11). Since then it has been used by mobile teams that regularly dive as deep as 250 ft (75 m). Dives have not been allowed to be repeated in less than 24 h.

The 1964 Diving Manual (12) reissued Schedules I and II of 1958 as a combined table separated by what was called the *limiting line*. The same advisory notes and repetitive dive rules applied. Schedule III was withdrawn from general use.

The schedules were metricated for the 1972 Diving Manual (13); they were unchanged beyond the conversion of feet to meters. Schedule I became Schedule 11, Air Table; old Schedule III reappeared as Schedule 13, Deep Air-Oxygen Table, and also, for the first time with air stops actually printed, as Schedule 12, Deep Air Table. The repetitive dive rules remained unchanged until 1975 (14), when the time limit within which the combined dive rule was applied was reduced to 6 h providing the second dive did not exceed 140 ft (42 m). This enabled divers to work in successive 6-h tide periods. Any dive deeper than 140 ft (42 m) or below the limiting line for shallower depths precluded any further diving deeper than 30 ft (9 m) for 12 h. Within these rules the limit on the number of repetitive dives was lifted.

The Royal Naval Physiological Laboratory, or RNPL, now the Admiralty Marine Technology Establishment Physiology Laboratory, or AMTE (PL), produced two new schedules in 1968 for dives as deep as 250 ft (75 m) with either air or oxygen stops (15). They were based on more recent Hempleman theories that had earlier been tested extensively on compressed air workers in the 1966 Blackpool Trial Schedules. These schedules were very safe in use; however, the Fleet rejected them on the grounds that the no-stop times were shorter than those already known to be safe in Royal Navy Schedule 11 (Air Table), and also that the

decompression times were unacceptably longer than those known to be safe or only marginally unsafe in Royal Navy Schedule 11.

A totally new method for calculating the decompression stops for repetitive dives was introduced. Its advantage was the simplicity of its rules: for a surface interval of less than 2 h, decompress for the combined dive time at the deepest depth; for a surface interval between 2 and 4 h add half the first dive time, for 4 to 8 h add ¼, and for 8 to 16 h add ⅛ of the first dive time to the second dive time and use that time for the deepest depth. This method was successful on trial.

In 1972 a metric edition (16) of this schedule from 75 m (246 ft) was produced in increments of 5 m for depth and stops, but it was apparently totally recalculated with different criteria. Most of the old no-stop dive times reappeared, the majority of dives had greatly reduced stop times, and the limiting line concept reappeared. The same repetitive dive rules were presented, with added flexibility. If both dives were above the limiting line and shallower than 40 m, then for a surface interval between 4 and 6 h, ¼ of the first dive time was added. After 6 h the previous dives could be discounted. How extensively and vigorously this schedule and its rules have been tested has not been published.

U.S. Navy schedules

It is presumed that it was French who introduced the 1907 Haldane schedules to the U.S. Navy along with the repetitive dive rules. French (17) extrapolated from these schedules for the salvage of the U.S.S. *F-4*, which lay in 306 fsw. These decompressions were only moderately successful. Haldane-type schedules, the Bureau of Construction and Repair (C. & R.) Schedules (18), were introduced and remained in use until 1937.

As a result of submarine escape experiments Hawkins et al. (19) suggested a revision of the C. & R. schedules based on a reduction of the original five half times to three. Yarbrough (20) calculated and tested these schedules using revised Haldanian criteria. They were introduced to the Fleet in 1937.

In 1945 Van der Aue et al. (21) tested the Yarbrough schedules and found them wanting in the longer and deeper working dives between 100 ft for 85 min and 170 ft for 30 min. New schedules were produced by des Granges et al. (22) in 1956 using six half times and an ascent rate of 60 ft/min. They were tested in 609 dives as deep as 190 ft. Exceptional exposure schedules for longer times and as deep as 300 ft were produced in 1957 (23). They were issued to the Fleet as two schedules in 1960 and subsequently were combined as the U.S. Navy Standard Air Decompression Table.

Before this table was introduced the repetitive dive procedure was to add the dive times of the repeated dives and do the stops for that summed dive time for the current dive depth, and to ascend at 25 ft/min. It was held that repetitive diving was only an emergency procedure (24).

The current U.S. Navy repetitive dive procedure, introduced in 1957, works by giving every dive that requires stops, as well as a wide range of no-stop dives, a repetitive group designation letter based on the calculated residual nitrogen in the tissues. This letter is used in the Residual Nitrogen Timetable for Repetitive Air dives for surface intervals of less than 12 h. The table is read horizontally to the appropriate surface interval; the column in which the surface interval appears names the Repetitive Group Designator (a letter). This designator is used to determine from the Residual Nitrogen Timetable the time that should be added to the dive time of the current dive to find the correct stops. The 62 originally tested pairs were done according to this scheme and were found to be safe (24).

French Navy schedules

Prior to 1961 the French used a metric version of the U.S. Navy schedule. The schedule of the Groupe d'Études et de Récherches Sous la Mer (GERS schedule) in use since 1961 (25) covers depths to 85 m (279 ft); its calculation was based on three tissue half times. The repetitive dive rules devised by GERS have a form similar to the U.S. Navy method. Each dive is given a coefficient to use with tables to determine the reduction in residual nitrogen resulting from surface interval time and the additional time presumed to have been spent at the depth of the second or subsequent dive.

No-stop dives

A convenient point to start discussion of no-stop dives is the infinite dive—the saturation depth that still permits direct surfacing. In a small series of dry dives, 12 h at 33 ft (10 m) still permitted direct surfacing, but from 35 ft (11 m) or deeper, occasional bends occurred (26). Tunnel workers exposed for 8 or more hours to pressures exceeding 31 ft experienced bends at a rate of $< 0.5\%$ with no-stop decompression from a depth range of 31.4 to 38.2 ft in a total of 7979 exposures (27).

There are three published accounts (19, 28, 29) of in-water no-stop working dives for humans (Table 1). Two of the experiments approached depth and time incrementally (19, 27), while the third (29) approached the no-stop time from a longer time but studied the depths in random order. All three could be at risk to acclimatization. Both the American studies were in a wet compartment chamber with a mean water temperature of about 19°C. Albano's dives were in sea water with a temperature range of 14°C–22°C (28). The decompressions done by Hawkins et al. (19) used either air or oxygen; oxygen could have provided some protective effect.

The times listed in Table 1 were those at which no symptoms or the mildest symptoms of decompression sickness occurred. The Albano (28) and Van der Aue et al. (29) dives are essentially the same down to about 130 ft. Thereafter, only Albano (28) and Hawkins et al. (19) results are comparable. The criteria for defining a safe dive may have differed between the experiments. Van der Aue et al. (29) cut back the times every time there was a mild or transient complaint, whereas the others had a more severe end point. With this consideration and the several other differences in method it would be fair to conclude that the results from all three trials are essentially the same. From these data a practical limit of no-stop dives for humans can be determined. For depths up to 185 ft the Van der Aue et al. (29) times seem to be representative because of their more severe criteria for safety.

The French (Berry et al., Ref. 25) no-stop times are very similar to those found by Albano (28) until deeper than 115 ft (35 m). British no-stop dive times are based on theory, and few comprehensive test dives have been made with their use. In schedule development, the no-stop times were modified as dictated by calculations done to remedy the schedules that failed (6–8). The published American no-stop dive times are the rounded-down results of the work of Van der Aue et al. (29). The published no-stop dive times are summarized in Table 2.

METHOD

The trials reported were carried out either in the wet compartment of the Deep Trials Unit (DTU) or at sea anywhere between Malta and northern Scotland between 1961 and 1969. The open sea trials were done between June and November and were generally conducted without using a submersible decompression chamber.

TABLE 1

PRACTICAL OBSERVATIONS FOR NO-STOP AIR DIVING

Depth (Feet) (Meters)	40	50	60	70	80	82 25	90	98 30	100	110	115 35	120	130	131 40	140	148 45	150	160	164 50	167	170	180 55	185 60	197	200	213 65
Time (min)																										
Hawkins et al.																										
50 ft min^{-1}	-	-	-	-	-	-	-	-	37	-	-	-	-	-	-	-	18	-	-	17	-	-	14	-	13	-
Van Der Aue et al.																										
25 ft min^{-1}	205	105	73	55	44	-	36	-	26	23	-	18	16	-	14	-	11	9	-	-	7	-	5	-	-	-
Albano																										
20 m min^{-1}	-	-	-	-	-	42	-	31	-	-	24	-	-	20	-	17	-	-	14.5	-	-	12.5	-	11.5	-	10

References used: Hawkins et al. (19); Van der Aue et al. (29); Albano (28).

TABLE 2
PUBLISHED NO-STOP DIVE TIMES

Depth of Dive, ft	Depth of Dive, m	No-Stop Dive Times, min: U.S. Navy 1957	Royal Navy 1956	RNPL* 1972	French 1977
33	10	–	–	230	–
35	–	310	–	–	–
40	12	200	135	–	–
50	15	100	85	80	–
60	18	60	60	–	70
–	20	–	–	45	60
70	21	50	40	–	–
80	24	40	30	–	45
–	25	–	–	25	40
90	27	30	25	–	–
100	30	25	20	20	30
110	33	20	17	–	–
–	35	–	–	15	25
120	36	15	14	–	25
130	39	10	11	–	–
–	40	–	–	11	10
140	42	10	9	–	10
150	45	5	8	9	5
160	48	5	–	–	5
–	50	–	–	7	5
170	51	5	–	–	–
180	54	5	–	–	–
–	55	–	–	6	5
190	57	5	–	5	5

*RNPL, Royal Naval Physiological Laboratory.

Descent times were kept to a minimum of 75 ft/min and all dives included work in the form of swimming or weightlifting while on the bottom. Timing was always by stopwatch and in duplicate. Open-water depth was fixed by a free-hanging shot.

Divers used either open-circuit equipment with air supplied by hose or a self-contained semiclosed-circuit rig with oxynitrogen mixtures. When mixtures were used the Royal Navy equivalent air depth rules (13) were applied to determine the decompression required. For dives as deep as 140 ft (42 m), 40%/60% oxynitrogen mixtures were used. The equivalent air depths for these dives were 10 ft (3 m) shallower than the true depth in the range 70–140 ft (21–42 m). Deeper than 140 ft (42 m), 32.5%/67.5% oxynitrogen was used and no correction was made because the inspired $P_{I_{O_2}}$ is essentially that of air at the same depth as a result of oxygen consumption from the rebreathing bag. In the triple no-stop dive series 32.5%/67.5% mixture was used for all dives.

In the tables summarizing the trials, notation is made of absence of or degree of decompression sickness reported (Table 3). In Table 4 provision is made for recording results if the same pair of divers repeated the dives on two or more consecutive days.

Where statistical significance is discussed, the test used was chi-square and the minimum level of significance required was $P < 0.05$.

TABLE 3
TESTS OF SINGLE DIVES USING ROYAL NAVY AIR TABLE SCHEDULE 11, WITH OPEN-CIRCUIT EQUIPMENT

Location	Depth ft	Depth m	Time, min	No. of Dives	DCS*	Comment
Deep Trials Unit	120	36	20	10	0**	Dives done randomly over 2
June 1965 to	120	36	40	10	0	years by divers in normal
Sept. 1967	140	42	30	10	1B†, 1N‡	state of acclimatization.
	160	48	25	10	0	
	180	54	15	34	2B	
	180	54	20	69	2B, 1N	
Open water	160	48	25	8	2N	180′ × 19 min dives done over
July 1961 to	170	51	20	4	1B, 1N	5 days and the remainder
Oct. 1967	180	54	15	10	2B, 3N	done over 8 days.
(H.M.S. *Reclaim*)	180	54	19	10	2B	
	180	54	20	2	1B	
Open water	130	39	35	6	2N	Dives done in order of
Oct. 1969 to	140	42	30	6	1N	increasing depth over 6
Nov. 1969	150	45	25	6	2N	days possibly permitting
(H.M.S. *Reclaim*)	160	48	25	6	0	acclimatization.
	170	51	20	6	0	
	180	54	20	6	0	

*DCS, decompression sickness. **0, no complaints at all. †B, pain-only bends that required treatment. ‡N, niggle or marginal aches that resolved spontaneously.

Single Dives with Royal Navy Air Table, Schedule 11

In view of the doubt regarding the effectiveness of the deeper and longer dives, a selection between 120 and 180 ft (36 and 56 m) was tested with open-circuit air equipment. These trials occurred at intervals over an 8-year period (1961–1969). The results confirmed that the part of Schedule 11 (see Table 3) deeper or longer than 140 ft for 15 min, was unsatisfactory, having an incidence rate of 5.6% bends requiring treatment.

A major problem with any decompression study is the acclimatization of divers that comes with daily diving. A possible effect of acclimatization may be seen in the second series of open-water dives, which began shallow and worked deeper each day. At the start there were a few niggles, but then the dives became trouble free. The difference between the two open-water groups was not significant, however.

Repetitive dives using Royal Navy Air Table, Schedule 11

A series of tests of repetitive dives (see Table 4) was carried out over a 13-month period (1965–1966) in the Deep Trials Unit and the Mediterranean. The objective was to see what margin there was, if any, which would allow safe contravention of the 12-h rule, at least for specific sections of the schedule. Pairs of dives were conducted to the same depth for the same time with surface intervals of 200, 120, or 100 min. The later dives were repeated twice instead of once. All dives had the standard decompression for the current dive time at depth or

TABLE 4

REPETITIVE DIVING TRIALS USING THE ROYAL NAVY AIR TABLE SCHEDULE 11, CONTRARY TO THE COMBINED DIVE RULES

Location	Depth, ft	Depth, m	Time, min	No. of Dives/Set	Surface Intervals, min	No. of Sets of Dives[a]	Stops	Gas Used	DCS[b]
Deep Trials Unit Aug 1965–Apr 1966	180	54	20	2	200	13	yes	mix	2B[c]
	160	48	20	2	200	24	yes	mix	2B
	140	42	20	2	200	30	yes	mix	2N[d]
	100	30	20	2	200	10	nil	mix	0[e]
	80	24	20	2	200	10	nil	mix	0
	140	42	20	2	200	4×2	yes	mix	0
	160	48	20	2	200	4	yes	air	0
	140	42	10	2	100	9	yes	air	0
	140	42	10	2	100	5	nil	mix	0
	140	42	10	3	100	30	nil	mix	1N
	130	39	10	3	100	5	nil	mix	0
	110	33	10	3	100	7	nil	mix	0
	140	42	10	3	100	2×2	nil	mix	0
Open Water May 1966–Sep 1966	140	42	20	2	200	52	yes	mix	3N
	140	42	10	3	120	17	nil	mix	2B
	130	39	10	3	120	2	nil	mix	0
	120	36	10	3	120	2×2	nil	mix	2B

[a]Same pair of divers repeating the dive on successive days, i.e., 4 days = 4 × 2; 2 days = 2 × 2. [b]DCS, decompression sickness.
[c]B, pain-only bends that required treatment. [d]N, niggle or marginal aches that resolved spontaneously. [e]0, no complaints at all.

equivalent air depth, regardless of whether they were first, second, or third dives. The majority of the dives were done with oxynitrogen mixtures.

The dives done in the DTU deeper than 140 ft (42 m) for 15 min had a bends rate of less than 15% for pairs of dives, if the surface interval was 200 min. This was not significantly greater than for the single dives. At depths of 140 ft (42 m) or shallower in the DTU with durations of 15 min or less there were only a few minor problems not requiring treatment. Dives at 140 ft for 20 min were also successfully done twice a day for four consecutive days by the same pair of divers. Ten-minute dives could be repeated with relative inpunity for up to a total of three dives with surface intervals of only 100 min.

Transferring to open water and extending the interval to 120 min resulted in two bends in the 140-ft series of triple dives. As with the single dive series, although the incidence of bends was higher in the open water than in DTU, a level of significance was not achieved.

There appears, however, to be scope to do pairs of 10-min dives as deep as 140 ft (42 m) in open water, with an interval of 120 min, without adding to the decompression from the second dive.

Repetitive dives with the RNPL 1968 Air Table

The RNPL 1968 Table (see Table 5) was extensively tested at sea with both air and air/oxygen stops in a range of dives up to 200 ft (60 m) deep and durations of up to 60 min. They were found to be trouble free.

The repetitive dive procedure was tested with 40 dives each in both the DTU and the open sea. All the dives were done with open-circuit air apparatus used between 140 ft (42 m) and 180 ft (54 m) in the permutations shown in Table 5. Only one instance of minor untreated decompression sickness occurred after surfacing from the second of a pair of dives to 140 ft (42 m) with a 2-h surface interval.

The simple method for determining the stops required for repetitive dives to the same depth with this schedule seems to be satisfactory.

TABLE 5

TEST OF ROYAL NAVAL PHYSIOLOGICAL LABORATORY 1968 AIR TABLE REPETITIVE DIVE SYSTEM

Location	Depth, ft	Depth, m	Dive time, min: Dive 1	Dive time, min: Dive 2	No. of Successive Dives	Surface Intervals, h	No. of Sets of Dives	DCS*
Deep Trials Unit	180	54	20	15	2	4	10	0**
Nov. 1968–	180	54	15	15	2	4	10	0
Apr. 1969	180	54	20	15	2	2	10	0
	140	42	20	20	2	2	10	0
Open Water	180	54	20	15	2	4	10	0
Jun. 1968–	180	54	20	15	2	2	10	0
Jul. 1969	160	48	20	15	2	2	10	0
	140	42	20	15	2	2	10	1N†

*DCS, decompression sickness. **0, No complaints at all. †N, niggle or marginal aches that resolved spontaneously.

TABLE 6
TEST OF U.S. NAVY REPETITIVE DIVE SYSTEM

Location	Depth, ft	Depth, m	Time, min	No. of Successive Dives	Surface Intervals, h	No. of Sets of Dives	DCS*
Deep Trials Unit	180	54	10	2	4	11	0**
Jul. 1967–	160	48	10	2	4	10	0
Aug. 1968	140	42	10	2	4	10	0
	140	42	10	3	4	6	0
Open Water	160	48	10	2	4	10	0
Oct. 1967–	140	42	10	2	4	10	0
Nov. 1967							

*DCS, decompression sickness. **0, no complaints at all.

Repetitive dives with the US Navy Dive Schedule

A total of 57 sets of repetitive dives were performed using the U.S. Navy Schedule, both in the DTU and the open sea using open-circuit compressed air equipment (see Table 6). Paired and tripled dives of 10 min to the same depth were repeated with 4-h intervals at depths between 140 ft (42 m) and 180 ft (54 m). There were no decompression problems.

Triple no-stop dives

Certain groups of divers have to do frequent very short dives to depths down to about 147 ft (45 m). The depths may be quite random, but 2- or 3-min bottom time is all that is required (see Table 7). This study investigated the possibility of doing 5-min dives to combinations of

TABLE 7
TRIPLE 5-MINUTE NO-STOP DIVE EXPERIMENT

Location	Depth, ft (m)	No. of Sets of Dives	Mean Descent Rate, ft/min	Mean Descent Rate, m/min	DCS*
Chamber	All Permutations of	27	99	30	1?N**
May 1970	82(25), 115(35), 147(45)				
(H.M.S. *Vernon*)					
Open water	82(25), 115(35), 147(45)	12	–	–	0†
(cold)	147(45), 115(35), 82(25)	12	94	28	0
Jul. 1970,	147(45), 147(45), 147(45)	12	–	–	0
(Scotland)					
Open water	82(25), 115(35), 147(45)	10	–	–	0
(warm)	147(45), 115(35), 82(25)	10	80	24	0
Jul. 1970,	147(45), 147(45), 147(45)	10	–	–	1B‡
(Malta)					

*DCS, decompression sickness. **N, niggle or marginal aches that resolved spontaneously. †0, No complaints at all. ‡B, pain-only bends that required treatment; occurred after 2 dives.

three depths, 82 ft (25 m), 115 ft (35 m), and 147 ft (45 m), with a 1-h interval between leaving the bottom and starting the next dive, until three no-stop dives were completed by the same diver.

According to the Royal Navy repetitive dive rules, if either of the first two dives is to 147 ft (45 m), stops will be required during the ascent from the second dive. If any dive of the triple is as deep as 115 ft (35 m), the third dive will require stops.

A pilot study was conducted in a dry compression chamber with resting divers. Every permutation of the three dives was carried out in a random order, e.g., ACB, CCC, BAC, BBA, CBB, etc., giving 27 triple dives in all, done by 12 divers without a significant problem.

The experiment was then taken to sea in two parts; one trial was done in warm water (~19°C) by 10 divers. The triple dives were three combinations, either working deeper (ABC), or working shallower (CBA), or all at the deepest depth (CCC). Each group was to do 12 of each triple dive in an order randomized by the throwing of dice.

The cold water group completed their dives with complete freedom from decompression sickness. The warm water group stopped the experiment when the diver doing the 10th 147-ft (45-m) triple dive got a limb bend after his second dive. By this stage other divers had begun to report transient aches at the end of the triple dives. The afflicted diver had completed four triple dives in the preceding 7 days.

The mean bottom time for these dives ranged between 3 min 17 s and 4 min 8 s, depending on depth. The total range was 0 min 22 s to 4 min 25 s. According to the rules, the dive that led to the bend would have required 5 min of decompression. The third dive would have needed 10 min of decompression.

The cold water team was in a very high state of acclimatization to diving compared with the warm water team, and this perhaps explains the different experience of the two groups.

DISCUSSION

The Royal Navy Schedule 11 (Air Table) has an unacceptable risk of about 6% bends incidence if dived to the limit deeper than 140 ft (42 m) for durations greater than 15 min. The rest of the schedule evidently has a sufficient safety margin to permit complete disregard of the first of a pair of dives if the surface interval is 2 h or more for dives up to 10 min. As a result of the work described here, the Royal Navy repetitive dive rules were relaxed in 1975 to allow dives shallower than 42 m without additional penalty once the surface interval exceeded 6 h. There still appears to be sufficient latitude to permit some further relaxation of the rule.

Both the U.S. Navy and RNPL (1968 Table) repetitive dive rules were effective on the selected repetitive dives using the appropriate decompression tables. Two comparisons were made applying the two methods for calculating the required loading for a second or subsequent dive to the same or similar depths. First (see Table 8), the Royal Navy combined dive rule, U.S. Navy rules, and RNPL rules were applied to each respective air decompression schedule for some of the dives reported here. The surface intervals all had 1 min added to give full advantage to the RNPL rules. The exercise was then repeated using the U.S. Navy Standard Air Decompression Schedule alone (Table 9), but with a different set of dives and surface intervals. When the repeated dives are all to the same depth the majority of the dives result in similar decompression whichever system of rules is applied. If, however, the dives are to moderately different depths the added penalty of the RNPL system is greater than the U.S. Navy system. This is purely because the deeper of the two depths has to be taken to get the stops. Interestingly, taking the mid depth between the dives again produces similar stops.

TABLE 8
TOTAL DECOMPRESSION, IN MINUTES, FROM FINAL DIVE

Depth of Dive, ft	Depth of Dive, m	Length of Dive, min	No. of Dives	Surface Interval	U.S. Navy Table			Royal Navy Table			RNPL* 1972 Table		
					Royal Navy Combined	U.S. Navy Repetitive	RNPL Repetitive	Royal Navy Combined	U.S. Navy Repetitive	RNPL Repetitive	Royal Navy Combined	U.S. Navy Repetitive	RNPL Repetitive
147	45	5	2	1 h 1 min	3	5	3	5	10	5	15	15	15
147	45	5	3	1 h 1 min	5	11	5	10	20	10	15	25	15
140	42	10	3	2 h 1 min	28	18	8	30	20	15	NA**	55	25
130	39	10	2	2 h 1 min	6	6	3	10	10	5	15	15	10
160	48	20	2	3 h 1 min	71	40	40	75	45	45	NA	95	95
180	54	20	2	4 h 1 min	NA	53	40	NA	65	45	NA	115	85
180	54	10	2	4 h 1 min	NA	12	12	NA	30	20	55	55	20
110	33	20	2	1 h 1 min	24	24	24	25	25	25	75	75	75

*RNPL, Royal Naval Physiological Laboratory. **NA, not allowed.

TABLE 9

TOTAL DECOMPRESSION TIME, IN MINUTES, FOR REPETITIVE DIVES BY THE U.S. NAVY STANDARD AIR DECOMPRESSION SCHEDULE

Dive		Surface				
Depth, ft (m)	Time, min	Interval, h	Royal Navy Combined	U.S. Navy Method	RNPL* Method	RNPL Using Mid Depth
100 (30)	20	1st dive	2	2	2	–
		1	17	17	17	–
		4	17	5	5	–
		6	17	5	2	–
		8	2	2	2	–
120 (36)	20	1st dive	2	2	2	–
		1	32	32	32	–
		4	32	16	16	–
		6	32	16	6	–
		8	2	6	2	–
140 (42)	20	1st dive	2	2	2	–
		1	8	8	8	–
		4	8	4	4	–
		6	8	4	4	–
		8	2	4	4	–
180 (54)	10	1st dive	6	6	6	–
		1	26	26	26	–
		4	26	12	12	–
		6	26	12	12	–
		8	26	12	12	–
180 (54)	20	1st dive	26	26	26	–
		1	NA**	93	93	–
		4	NA	53	53	–
		6	NA	40	40	–
		8	NA	40	40	–
1) 180 (54)	10	1st dive	6	6	6	6
2) 120 (42)	10	1	26	18	26	16
		4	26	4	12	7
		6	26	4	12	7
		8	26	4	12	7
1) 140 (42)	20	1st dive	8	8	8	8
2) 120 (36)	20	1	46	48	46	37
		4	46	16	28	23
		6	46	16	18	12
		8	8	16	18	12

*RNPL, Royal Naval Physiological Laboratory. **NA, not allowed.

The similarity of outcome with these two methods when the repeated dives are to similar depths is a significant comment on their relative complexities. The RNPL system is quicker and easier to use than the U.S. Navy system, but it presently lacks the flexibility of the latter for handling repetitive dives to very dissimilar depths. Simplicity is one of the keys to safety and this should be remembered by those who undertake any future work on repetitive diving. This point may be argued by those who believe that electronic decompression computers will be the norm in the future. In the years 1972 and 1973 U.S. Navy divers did about 100 repetitive dives (<0.2% of all dives; see Ref. 30). Even this figure could be overestimated, as it is believed that some no-decompression diving is not reported (31). In view of the apparent requirement elsewhere for repetitive dives, this small number may reflect a reticence on the part of U.S. Navy divers to use such a cumbersome system.

When choosing decompression schedules, working divers are greatly influenced by efficiency or by the least amount of decompression penalty. This remains the key factor until problems of increasing cost and delay caused by decompression sickness become important. The RNPL 1968 Schedule (15) was certainly safe but clearly inefficient as a result of the considerable and apparently unnecessary increases in the decompression times. Not enough is known of the 1972 schedule (16) for comment beyond the fact that it is more efficient, although it may still be overcompensating for the known weaknesses of Royal Navy Schedule 11 (Air Table) (13). The RNPL schedules are lauded (16) for the low incidence of dysbaric osteonecrosis, but there is little evidence that either the Royal Navy or U.S. Navy schedules previously had that problem.

It was shown to be possible for a highly acclimatized group working in cold water to do up to three 5-min dives as deep as 147 ft (45 m) separated by a 1-h interval without the need for decompression stops. It remains unknown whether the apparent failure of the group working in warm water was due to either a lack of acclimatization or a thermal effect. The only tentative conclusion is that the frequency of these dives was greater than was compatible with safe decompression for an average group of working divers.

For emphasis on safety and practicality it would appear that the Van der Aue et al. (29) no-stop dive times are the nearest to an optimum. In current use they have been slightly shortened from times derived under severe constraints about what constituted a safe dive albeit in possibly acclimatized divers. In view of the past work, little stands to be gained by any new efforts to define new no-stop dive limits for divers.

Preparing trials of decompression is difficult because numbers of divers are limited; therefore in any series they tend to become acclimatized, as suggested in the single air dive trials of the Royal Navy Air Table in 1969. In the final testing of a schedule the dives need to be randomized and carried out by as many participants as possible. In this series of trials there is no statistical support for the idea that transfer of a schedule from simulated wet diving facilities to the open sea leads to an increase in the incidence of decompression sickness. The data available for comparison in Table 3 covered the 161 dives done to 140, 160, and 180 ft. There were 5 bends in 123 dives in the DTU and 3 bends in 38 dives at sea. An additional 4 bends at sea would have been required to indicate a significant difference between the two conditions at $P < 0.05$. If the incidence at sea had remained the same and the number of dives tripled to 9 bends, there would still have been no significant difference. It is clear that with the customary small samples available from decompression trials that incidence rates have to differ markedly to be significant.

The opinions and assertions contained herein are the private ones of the authors and are not to be construed as official or reflecting the views of the Royal Navy or the United States Navy Department or the naval services at large. The editorial assistance of Ms. D. Cave is appreciated.—*Manuscript received for publication December 1981; revision received February 1982.*

Leitch DR, Barnard EEP. Observations sur la remontée sans palier et sur les plongées successives à l'air ou au nitrox. Undersea Biomed Res 1982; 9(2):113–129.—Les fondements historiques des tables de décompression des marines respectives de Grande Bretagne et des Etats-Unis sont présentés en insistant particulièrement sur les règles observées pour les plongées successives. Les remontées sans palier sont également traitées. On présente une série de tests de la table à l'air de la Royal Navy (RN) en plongées simples et en plongées successives. Sur la base d'une sélection de plongées, on a aussi evalué les règles de plongée répétitive de l'U.S. Navy (USN) et 1968 du Royal Naval Physiological Laboratory (RNPL) en fonction de leurs tables respectives. Ce qui est préconisé par les deux méthodes est remarquablement semblable dans le cas de plongées successives effectuées à des profondeurs voisines. Dans le cas de profondeurs tres inégales, il n'y a pas de comparaison. Le système RNPL présente une louable simplicité mais il lui manque la souplesse d'emploi du système USN dans le cas de plongées successives à des profondeurs différentes. Sont présentées des observations sur les résultats d'une expérience de trois plongées sans palier successives. On en conclut qu'il y a peu à retirer d'une étude expérimentale plus poussée des temps de plongée sans palier.

décompression à l'air
remontée sans palier
plongées successives

REFERENCES

1. Boycott AE, Damant GCC, Haldane JS. The prevention of compressed air illness. J Hyg (Camb) 1908; 8:343–443.
2. Admiralty Deep Diving Committee Report. London: HMSO, 1933.
3. Davis RH. Deep diving with the Davis submerged decompression chamber. Oxy-helium diving by the Royal Navy. The Siebe, Gorman & Co. decompression tables. In: Deep Diving and Submarine Operation. London: St. Catharine Press, 1935: 136–179.
4. The Diving Manual, Admiralty (Gunnery Branch) B.R. 155/43, London: HMSO, 1943.
5. Theory of Diving—Part I. In: Royal Navy Diving Manual. Admiralty (Gunnery Branch) B.R. 155 C. London: HMSO, 1956.
6. Rashbass C. Investigation into Decompression Tables, Report VI, UPS 171 RNPL 9/55. London: HMSO, 1955.
7. Hempleman HV, Crocker WE, Taylor HJ. Investigation into Decompression Tables, Report III, UPS 131 4/52. London: HMSO, 1952.
8. Crocker WE. Investigations into Decompression Tables. Report IX, UPS 171 RNPL 57/902. London: HMSO, 1957.
9. Diving Manual, Amendment No. 3. Admiralty Fleet Order P.109/58. London: HMSO, 1958.
10. Crocker WE. In: Proposals for Applying the New Standard Table to Surface Decompression and Combined Dives. London: HMSO, UPS 175, RNPL 3/58, 1958.
11. Deep Diving—Part V. In: Royal Navy Diving Manual. London: HMSO, 1957.
12. Diving Manual, Admiralty (Weapons Department) B.R. 155. London: HMSO, 1964.
13. Diving Manual B.R. 2806, Ministry of Defence. London: HMSO, 1972.
14. Diving Manual B.R. 2806, Change 2. London: HMSO, 1975.
15. Air Diving Tables. Royal Naval Physiological Laboratory, Alverstoke, Hants. London: HMSO, 1968.
16. Hempleman HV, Taylor BA. In: Air Diving Tables 1972. Alverstoke: Royal Naval Physiological Laboratory, Report No. 7/73. Directorate of Research (Underwater) MOD PE. London: HMSO, 1973.
17. French GRW. Diving operations in connection with the salvage of the USS "F-4." US Nav Med Bull 1916; 10:74–91.
18. U.S. Navy Diving Manual. Washington, DC: U.S. Navy Bureau of Construction and Repair, 1924.
19. Hawkins JA, Shilling CW, Hansen RA. A suggested change in calculating decompression tables for diving. US Navy Med Bull 1936; 34:47–52.
20. Yarbrough OD. Calculation of Decompression Tables. In: Research Report and Endorsing Letters. Washington, DC: U.S. Naval Experimental Diving Unit, 1937.
21. Van der Aue OE, Brinton ES, Kellar RJ. Surface decompression, derivation and testing of decompression tables with safety limits for certain depths and exposures. Washington, DC: U.S. Navy Experimental Diving Unit, Report No. 1, 1945.
22. Des Granges M. Standard Air Decompression Table. Washington, DC: U.S. Navy Experimental Diving Unit 1957, (5–57).

23. Workman RD. Calculation of Air Saturation Decompression Tables. Washington, DC: U.S. Navy Experimental Diving Unit, 1957 (11–57).
24. Des Granges M. Repetitive Diving Decompression Table. Washington, DC: U.S. Navy Experimental Diving Unit, 1957, (6–57).
25. Berry Y, Gavarry P, Hubert JP, Le Chuiton J, Parc J. Tables de plongée a l'air. In: La Plongée et l'Intervention Sous la Mer. Grenoble, France: Arthaud, 1977:67–95.
26. Van der Aue OE, Kellar RJ, Brinton ES. The effect of exercise during decompression from increased barometric pressures on the incidence of decompression sickness in man. Washington, DC: U.S. Navy Experimental Diving Unit, 1949: 8–49.
27. Decompression sickness and aseptic necrosis of bone. Investigations carried out during and after the construction of the Tyne Road Tunnel (1962–66). Report of Decompression Sickness Panel, Medical Research Council. Br J Ind Med 1971; 28:1–21.
28. Albano G. Experimental research on the decompression of man I. Critical safety values of the pressure gradient during a direct ascent to the surface without stops. Med dello Sport 1961; 1:259–275.
29. Van der Aue OE, Kellar RJ, Brinton ES, Barron G, Gilliam HD, Jones RJ. Calculation and testing of decompression tables for air dives employing the procedure of surface decompression and the use of oxygen. Washington, DC: U.S. Navy Experimental Diving Unit, Report No. 1, 1951.
30. Berghage TE, Rohrbaugh PA, Bachrach AJ, Armstrong FW. Navy diving: who's doing it and under what conditions. Bethesda: Naval Medical Research Institute Technical Report. Report No. MPN10.03.2040 DAC 9, 1975.
31. Berghage TE, Durman D. U.S. Navy Air Decompression Schedule Risk Analysis. Bethesda: Naval Medical Research Institute Research Report. Report No. 80-1, 1980.