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Decompression after repeated dives

A. A. BÜHLMANN

Medical Clinic, University Hospital, Zürich, Switzerland

Bühlmann AA. Decompression after repeated dives. Undersea Biomed Res 1987;14(1): 59–66—Seventy-six men and 7 women performed a 2nd dive in a pressure chamber under dry conditions after intervals at the surface of 10, 30, 90, or 120 min. Of these, 35 persons performed a 3rd dive after an interval of 20 or 90 min (118 repeated dives). Air was the breathing gas during all phases of the tests. During exposure to overpressure the divers exercised on a bicycle-ergometer. The decompressions for dives 2 and 3 were the same as for the first dive. After the 2nd or 3rd dive, certain symptoms of decompression sickness of the skin occurred in 5 of the 118 exposures, and 1 diver complained of muscular aches. These results suggest that no general sensitization occurred after the 1st dive.We concluded that a slightly more conservative decompression with regard to ascent velocity and profile is feasible for repeated dives.

simulated air dives
calculation of decompression
minimal decompression
repeated dives
DCS skin
muscles

Complete equilibration of pressure among the respiratory gas (N_2), blood, and various tissues of the human body requires some hours to some days. The rate of equilibration between blood and tissues is influenced by the local blood perfusion. After every dive N_2 is released by the lungs long after the diver has reached the surface. If a 2nd dive is to be performed during this phase, the additional N_2 dissolved in the tissues must be considered during decompression. To prevent decompression sickness, a 2nd dive of the same duration and depth requires a longer decompression time than the first. The additional time needed decreases as the interval at the surface is increased (1, 2).

If physical work is undertaken during exposure to increased pressure, decompression takes longer than identical exposure without physical exercise (3). In accordance with the exponential curve of pressure equilibration, the uptake of inert gases is accelerated by physical work, especially at the beginning of exposure to overpressure. Dick and co-workers have shown recently that after very short dives with physical work, more N_2 is eliminated at the surface than after identical dives without work (4).

These results do not indicate whether the tolerance of tissues for overpressure of N_2 decreases after a 1st dive. This is an important point, especially for dives of short duration. It is conceivable that after the 1st dive otherwise symptomless bubbles in the tissue obstruct the capillaries and consequently slow the elimination of N_2. Thus, longer half-times result for the same tissue during decompression and also during the interval at the surface.

METHOD

The trials were carried out in a pressure chamber under dry conditions with 83 moderately trained sport divers (76 male, 7 female). Their mean age was 31.3 ± 6.2 yr, mean height 176.3 ± 7.8 cm, and mean weight 73.5 ± 7.8 kg. The divers breathed air during overpressure and at normal pressure at the surface. The temperature in the pressure chamber was constant (20 to 22°C); the O_2 concentration 20–21%. Depending on the available time, 80 W were performed on a bicycle ergometer for 6 to 10 min. The mean pulse rate during exercise at overpressure was 109 ± 11/min; the mean uptake of oxygen, measured at normal pressure was 1200 ± 100 ml/min.

Table 1 shows the results of the 5 series of experiments, each using 12 to 24 different divers. Decompression after the 1st dive was carried out continuously in the Series AA-40 for 12 persons and with conventional steps (12, 9, 6, 3 m) for 12 other persons as in all other trials. The pressure is given in absolute values (bar).

Decompression was calculated according to System ZH-L_{12} with 12 pairs of coefficients, as shown in Table 2 for real circumstances with regard to pressure and time. The initial pressure of N_2, P_{N_2}, was entered with 0.724 bar for all tissues, according to the mean atmospheric pressure in Zürich of 0.970 bar. The normal decompression tables valid for Zürich are calculated for safety reasons with + 0.20 bar (+ 2 msw) for each depth (2). Therefore, the depth for these trials was chosen 0.20 bar deeper than indicated in the corresponding table. The first dive of Series AA-40, in which the actual depth was 41 m, can be compared with the 39 m, 40 min bottom time in the table, which is realistic if the depth gauge of the diver indicates only 39 m in a real depth of 41 m.

Exposure to overpressure was such that for decompression the half-times of 8.0 to 109 min are critical; this is valid for most sport dives. Half-times of 30 to 150 min is for skin and the muscles, for which perfusion is altered more under the influence of work and ambient temperature than is that of other tissues. If the tolerances for these half-times are exceeded, symptoms of insufficient decompression of the skin, with red itching and swollen spots, can occur. If decompression of the muscles is insufficient, the subjects experience pain and subsequent tiredness (2). Symptoms of this ordinarily harmless decompression sickness of the skin and muscles are used in these experiments as criteria for insufficient decompression. Whether there is a critical phase for the elimination of N_2 was investigated by intervals at the surface of 10 to 120 min.

RESULTS

In the Series AA-13, AA-18, and AA-20, after the first dive, the subjects returned to the surface, without decompression stops, at a rate of 1.05 to 1.07 bar/min.

TABLE 1

SIMULATED REPETITIVE AIR DIVING, 1.0 BAR = 10 MSW

Trial	Depth, Bar Absol.	Compression Time, min	Bottom Time, min	Time to First Stop, min	Decompression stops, bar 2.2	bar 1.9	min 1.6	min 1.3	Total Ascent, min	Subjects Male, *n*	Subjects Female, *n*	Affected Subjects, *n*
AA-13 Rpt.												
1st Dive	5.1	2	11	—	—	—	—	—	3.9	9	3	0/12
Interval	1.0	—	120									
2nd Dive	5.1	2	58	2.7	8	15	27	51	103.7	9	3	1/12
AA-18 Rpt.												
1st Dive	4.5	2	16	—	—	—	—	—	3.3	11	1	0/12
Interval	1.0	—	30									
2nd Dive	4.5	2	20	3.0	—	—	—	13	16.0	11	1	2/12
AA-20 Rpt.												
1st Dive	4.2	2	18	—	—	—	—	—	3.0	13	2	0/15
Interval	1.0	—	10									
2nd Dive	4.2	2	22	2.4	—	—	2	17	21.4	13	2	0/15
Interval	1.0	—	20									
3rd Dive	4.2	2	13	2.7	—	—	—	15	17.1	13	2	2/15
AA-35 Rpt.												
1st Dive	5.4	3	32	3.0	2	5	11	26	47.0	20	—	0/20
Interval	1.0	—	90									
2nd Dive	4.8	3	23	3.0	—	—	3	15	21.0	20	—	0/20
Interval	1.0	—	90									
3rd Dive	5.1	3	22	3.3	—	—	4	19	26.3	20	—	0/20
AA-40 Rpt.												
1st Dive	5.1	3	37	2.7	2	5	13	27	49.7*	23	1	0/24
Interval	1.0	—	120									
2nd Dive	5.1	3	30	2.7	2	4	6	27	41.7	23	1	1/24

*12 subjects: Decompression with stops in 49.7 min from 5.1 to 1.0 bar. 12 subjects: Continuous decompression in 42.7 min from 5.1 to 1.0 bar, 2.7 min 5.1–2.2 bar, 2.0 min 2.2–1.9 bar, 4.0 min 1.9–1.6 bar, 6.0 min 1.6–1.4 bar, 11.0 min 1.4–1.2 bar, 17.0 min 1.2–1.0 bar.

TABLE 2

ZH-L_{12} TWELVE PAIRS OF COEFFICIENTS FOR 16 HALF-TIMES FOR NITROGEN

Compartment No.	N_2-½ t min	Coefficients	
		a	b
1	4.0	1.900	0.800
2	8.0	1.450	0.800
3	12.5	1.030	0.800
4	18.5	0.882	0.826
5	27.0	0.717	0.845
6	38.3	0.575	0.860
7	54.3	0.468	0.870
8	77.0	0.441	0.903
9	109.0	0.415	0.908
10	146.0	0.416	0.939
11	187.0	0.369	0.946
12	239.0	0.369	0.946
13	305.0	0.255	0.962
14	390.0	0.255	0.962
15	498.0	0.255	0.962
16	635.0	0.255	0.962

P ambient tolerated (bar) = (P_{N_2} tissue − a) ·b or

= P_{N_2} tissue · b − c

c = a · b

The calculated value of the tolerated ambient pressure is during decompression rounded upward to the first decimal place. Example: Compartment No. 7 P_{N_2} tissue = 1.950 bar, P amb. tol. = 1.289 = 1.30 bar. The atmospheric pressure at surface is rounded upward to the second decimal place. Example: P amb. tol. = 0.851 = 0.860 bar.

Comparable dives without decompression stops are frequently carried out by sport divers. The total times for the 1st dives of Series AA-35 also lie within the range of regularly equipped sport divers.

The values of P_{N_2} reaching the surface that are well tolerated according to the coefficients of Table 2 were slightly exceeded with the 1st dives for the N_2 half-times of 12.5 and 54.3 min (Table 3). During or shortly after the ascent 35 of the 83 subjects reported a brief sensation of formication in their arms (AA-13, 6/12; AA-18, 2/12; AA-35, 11/20; AA-40, 16/24). In no case, however, did clear symptoms of an insufficient decompression develop. The intervals of 30 min at the surface in Series AA-18 and only 10 min in Series AA-20 are shorter than the usual time of latency for the development of reliably recognizable symptoms of the skin.

With the decompression after the repeated dives the values of P_{N_2} for the N_2 half-times of 38.3 to 109 min reached at surface are somewhat above those in Table 2 (*see* Table 3). These decompressions close to the borderline have been intended to achieve comparable conditions for all dives.

After the 2nd dive in Series AA-13 and AA-18, 2 women and 1 man developed skin symptoms of the upper trunk and upper arms, respectively. The partly swollen red spots vanished spontaneously within a few hours. After the 2nd dive in Series AA-

TABLE 3

P_{N_2} IN THE TISSUE AT THE END OF DECOMPRESSION AT AN AMBIENT PRESSURE OF 1.0 BAR AS A FUNCTION OF THE HALF-TIMES

Compartment No.	2	3	4	5	6	7	8	9	10		
N_2-½ t, min	8.0	12.5	18.5	27.0	38.3	54.3	77.0	109.0	146.0	Affected	
Tolerated P_{N_2} ZH-L_{12}	2.700	2.280	2.093	1.900	1.738	1.617	1.548	1.516	1.481	Subjects	Organ
1st Dive											
AA-13 Rpt.	2.670	2.340	1.993	1.705	—	—	—	—	—	0/12	—
AA-18 Rpt.	2.660	2.405	2.065	1.775	1.547	—	—	—	—	0/12	—
AA-20 Rpt.	2.611	2.349	2.048	1.773	1.545	—	—	—	—	0/15	—
AA-35 Rpt.	—	—	—	1.630	1.682	1.632	1.508	1.365	—	0/20	—
AA-40 Rpt.	—	—	—	1.595	1.661	1.632	1.526	1.382	—	0/24	—
2nd Dive											
AA-13 Rpt.	—	—	—	—	1.367	1.496	1.562	1.530	1.466	1/12	Skin
AA-18 Rpt.	—	—	1.872	1.842	1.758	1.616	1.450	1.295	—	2/12	Skin
AA-20 Rpt.	—	—	1.765	1.806	1.749	1.629	1.469	1.336	—	0/15	—
AA-35 Rpt.	—	—	1.812	1.785	1.718	1.631	1.547	1.445	1.369	0/20	—
AA-40 Rpt.	—	—	—	1.630	1.663	1.634	1.575	1.453	1.418	1/24	Muscle
3rd Dive											
AA-20 Rpt.	—	—	—	1.650	1.656	1.618	1.535	1.418	1.313	2/15	Skin
AA-35 Rpt.	—	—	—	1.738	1.696	1.625	1.559	1.485	1.426	0/20	—

40, 1 man complained of muscle pains, which vanished during recompression to 2.5 bar (absolute) while breathing pure oxygen. In this case, decompression after the 1st dive was performed with steps according to Table 1 for a total of 49.7 min. After the 3rd dive in Series AA-20, discrete symptoms of the skin occurred in 1 woman and 1 man.

DISCUSSION

The tolerance toward an overpressure of N_2 was tested by these repeated dives, especially for those compartments with half-times for N_2 between 38.3 and 109 min and partly to 146.0 min. These compartments are represented mainly by the skin and muscles, which are variably perfused. No clear symptoms of insufficient decompression occurred after the 1st dive, although the decompression profiles were very close to the statistically determined tolerances. After the 2nd and 3rd dives, 6 of 118 exposed divers, 5.08%, had symptoms of an insufficient decompression of the skin or of the musculature. When all 1st dives undertaken in Zürich since 1972 are taken into consideration to evaluate the coefficients of Table 2, an indicence of 1.93% (7 of 362 persons) of symptoms of an insufficient decompression (skin, muscles, joints) was found (2, 5, 6). The present results suggest that with repeated dives the risk of decompression sickness of the skin and the musculature may be somewhat increased, if the coefficients of Table 2 are used.

It is interesting that in Series AA-20, the diver with the shortest surface intervals of 10 min after the 1st dive and 20 min after the 2nd, symptoms arose only some hours after the 3rd dive (Tables 1 and 3). With longer intervals at the surface the incidence was greater after the 2nd dive.

Not a single diver developed neurologic symptoms. Inasmuch as lesions of the skin usually are harmless, we conclude that decompression for repeated dives may be calculated according to the tolerances that are valid for 1st dives. Using the System ZH-L_{12}, the calculation is simple enough to be performed during the dive by a microprocessor, such as the DECOBRAIN (Divetronic Instruments AG, Winterthur, Switzerland). Hahn and coworkers conducted a series of repeated dives with physical work in a water tank. Decompressions were calculated using the System ZH-L_{12} and carried out with the DECOBRAIN. The authors also found a higher incidence of skin symptoms after the 2nd dive (7).

Additional safety measures necessary for real diving in water (compensation of not accurately measurable depth and pressure, extreme conditions such as currents, waves, physical effort) are achieved by a reduction of the coefficients in Table 2, particularly for the N_2 half-times, 12.5 to 109 min.

Comparison with the supplements of time for repetitive dives shows that the decompression performed in these trials after the 2nd and 3rd dives is considerably shorter than prescribed, for example, by the U.S. Navy for repetitive dives. In accordance with U.S. Navy standard tables (table for 110 ft of sea water [fsw]), ascent to surface may be done in 1.8 min in Series AA-20. For the 2nd dive decompression lasting 36 min is recommended, and for the 3rd dive, 74 min. In Series AA-35, decompression for the 1st dive has to follow the table for 150 fsw, 40 min bottom time and, accordingly, will be 59 min. For the 2nd dive, the U.S. Navy prescribes decompression of 86 min, and for the third dive, 97 min. Even when considering reasonable safety limits, these decompression times for the 2nd and especially for

the 3rd dive are unnecessarily long. United States Navy tables allow a rate of ascent of 1.8 bar/min for dives without decompression stops, which equals 60 fsw/min, whereas the System ZH-L_{12} allows an ascent rate of 1.0 bar/min. Using U.S. Navy tables, ascent to 6 m, then 3 m (20 and 10 fsw, respectively) is significantly faster for those dives with decompression stops. However, the stop at 3 m is longer than with the coefficients in Table 2.

Figure 1 shows the relationship between the P_{N_2} in the tissue and the tolerated ambient pressure for the N_2 half-time of 54.3 min, corresponding to U.S. Navy decompression tables and with the coefficients in Table 2. The coefficients of the System ZH-L_{12} were systematically tested not only at overpressure but also at altitude (5).

Courses of decompression of the British Navy differ from those of the U.S. Navy in that they prescribe deeper first steps of decompression with somewhat shorter stays at 3 m (2).

The long stop at 3 m according to U.S. Navy tables is responsible for a P_{N_2} for the half-times of 38.3 and 77.0 min at the end of decompression, somewhat below the values predicted by the coefficients in Table 2. It is possible that a fast initial decompression sensitizes tissues such as skin and muscles. After a long stop at 3 m, however, the critical decompression is mostly asymptomatic. If the fast first phase of decompression reduces the tolerance of the tissue to an N_2 overpressure, considerably longer durations of decompression and a slower initial decompression for repeated dives have a prophylactic effect.

CONCLUSIONS

The results of the present experimental dives make it probable that the calculation of decompressions for repeated dives can be performed with real values for pressure

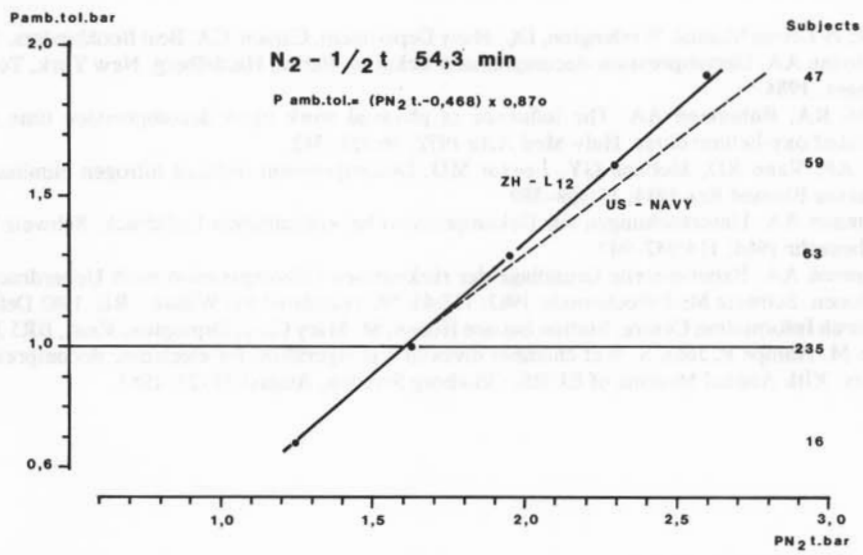

Fig 1. Tolerated ambient pressure (P amb.tol.) dependent on the calculated P_{N_2} in the tissue with a N_2 half-time of 54.3 min. The *line* corresponds to the coefficients of Table 2, tested for ambient pressures from 0.69 to 1.90 bar. *Broken line* corresponds to the profile of decompression of the U.S. Navy Standard Air Decompression Table.

and time, using the same tolerances as for the 1st dive. Neither in our investigations nor in the repeated dives of Hahn and coworkers did symptoms of an insufficient decompression of the CNS develop. Coefficients for the short half-times of N_2 in Table 2 also include a considerable safety margin for repeated dives. It is likely that a slightly more conservative decompression after the 1st dive than in the present trials would reduce to below 5% the incidence of skin and muscle symptoms after repeated dives.

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Bühlmann AA. La décompression après de plongées itératives. Undersea Biomed Res 1987; 14(1): 59–66.—Un total de 76 hommes et 7 femmes accomplirent une deuxième plongée dans un caisson hyperbare et sous conditions sèches après des intervalles de surface de 10, 30, 90, ou 120 min. De ces personnes, 35 plongèrent une troisième fois, après un intervalle de 20 ou 90 min. Le gaz respiratoire durant toutes les phases de l'évaluation était de l'air. Pendant la période de compression, les sujets firent de l'exercice sur bicyclette ergométrique. Les compressions pour les plongées itératives furent en tout point semblables aux premières plongées. Après la deuxième ou troisième plongée, certains symptômes cutanés de la maladie de décompression survinrent chez des 118 sujets, et une personne d'essai se plaignit de douleurs musculaires. Ces résultats sont à l'encontre d'une sensibilisation générale après une première plongée, ou une période d'élimination de l'azote de plusieurs heures. Il est conclu qu'une décompression un peu plus prudente concernant le profile et la vitesse de remontée est parfaitement réalisable pour les plongées itératives.

plongées simulées à l'air
calculation de la décompression
décompression minimale
plongées itératives
maladie de décompression de la peau
muscles

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