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Gas phase separation during decompression in man: ultrasound monitoring

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Neuman, T. S., D. A. Hall, P. G. Linaweaver, Jr. 1976. Gas phase separation during decompression in man: ultrasound monitoring. Undersea Biomed. Res. 3(2):121-130.–During two dive series, one to 132 fsw and one to 210 fsw, Doppler ultrasonic bubble detectors were used to monitor venous gas bubbles in divers during decompression and for 30 min thereafter. Various decompression schedules were used. Bubble scores were evaluated by independent listerners to tape recordings in a blind manner. A significant increase in bubble scores throughout the stages of decompression and postdecompression was demonstrated as well as a statistically significant relationship between bubble score and decompression sickness. A reduction in mean bubble score was found in divers who made an additional deep decompression stop that was unrelated to the extension of the decompression time. The implications of these finding are discussed.

ultrasound
bubble detection
decompression sickness

In 1907 Haldane, Boycott, and Damant proposed that the occurrence of decompression sickness (DCS) was governed by the ratio between final pressure and initial tissue inert gas pressure. Van der Aue, Keller, Brinton, Baron, Gilliam, and Jones (1951) advanced the science of decompression by the use of multiple critical ratios rather than the single Haldane ratio. Ratios of this type were utilized by des Granges in 1956 to calculate the current U.S. Navy Air Decompression Tables and, in 1965, Workman expanded the concept by presenting the multitissue, exponential absorbtion/elimination method used for the calculation of many current commercial diving tables.

The basic assumption common to all of the above theories and modifications is that inert gas is eliminated in the same exponential manner as it is absorbed; thus, the tables from des Granges and, indeed, most contemporary decompression calculations are based on the assumption that no gas-phase separation (bubble formation) occurs during asymptomatic decompression (Dwyer 1955; Workman 1969; Powell 1972a). Furthermore, inherent in a symmetrical exponential model without gas-phase separation is the requirement for a large initial pressure reduction at the start of decompression to creat a maximal pressure differential for inert gas elimination (Van der Aue, et al. 1951; Workman 1965.)

Bubble formation occurring during the initial or subsequent pressure reduction would alter the symmetry of the absorption/elimination curve and therefore, gas elimination would not necessarily be the reverse of the absorption process. As early as 1912 Hill suggested that the large initial pressure reduction of staged decompression was not beneficial. Hempleman (1963) postulated a "tissue-bubble complex" and suggested that the presence of bubbles can alter inert gas elimination by impeding blood flow.

Animal work with Doppler ultrasonic monitors (Spencer and Campbell 1968; Spencer, Campbell, Sealy, Henry, and Lindbergh 1969; Smith and Johanson 1970; Smith and Spencer 1970; and Powell 1972a,b; 1974) has demonstrated the presence of what are considered to be venous bubbles, prior to the onset of decompression sickness. Investigators have also detected venous bubbles in asymptomatic animals and human subjects (Evans, Barnard, and Walder 1972; Spencer and Johanson 1974; Powell and Johanson *in press*). Using the Doppler monitor, Spencer and Johanson (1974) found venous bubbles in men following U.S. Navy *no-decompression* dives. In addition, Nashimoto and Gotoh (*in press*) have detected venous bubbles following staged decompression in Japanese caisson workers. Hills (1966) postulated the presence of bubbles during virtually any significant decompression.

Just one study on human subjects has been published where bubble scores were evaluated during staged decompression (Smith and Johanson 1970) and only one study has had bubble scores evaluated independently (Powell and Johanson 1975). In work that we describe here we used the Doppler precordial bubble detector to examine the presence and formation of bubbles in human beings during and following decompression from hyperbaric exposures made under a rigidly controlled chamber environment simulating diving pressure.

METHODS

In order to verify the existence of asymptomatic gas-phase separation and to compare the appearance of bubbles with standard decompression profiles, a group of highly experienced U.S. Navy personnel were monitored with a 5 MH_z, Model AB Doppler precordial bubble detector (Spencer and Clarke 1972) during routine hyperbaric chamber operations. The mean age of the divers was 30.8 years (range 25-44), their weight 79.5 kg (range 61.3-90.9) and their ponderal index (as a quantitative measure of obestiy; Keys, Fidarza, Karvonen, Kimura, and Taylor 1972) was 2.43 kg-3/m (range 2.28-2.58 kg-3/m). Informed consent for the use of the Doppler during these dives was obtained from all of the subjects. The safety of the Doppler monitor has been previously demonstrated (Spencer and Campbell 1972).

Prior to compression all of the divers were instructed in the use of the Doppler unit. The exact position of the point yielding the best signal from the pulmonary artery was marked on their chests, insuring repeatable sensor placement. A predive recording of the Doppler signal was made as well as individual recordings just prior to decompression and at all decompression stops where time permitted. These recordings were numerically coded in a random fashion.

The first dive series consisted of 18 man-dives (6 dives, 3 divers per operation) to 210 fsw. Two individuals participated twice in this series. The dives were made in the deck decompression chamber (DDC) of the U.S. Navy MK II MOD O Deep Dive System. Air was the breathing medium throughout the operation. Throughout the bottom phase the subjects were responding to psychological questionnaires. Temperature and humidity were maintained within the comfort range for the divers. There was no water immersion. After a 50-min total bottom time (TBT; i.e., time of compression plus time at depth) the subjects were decompressed according to one of three profiles. Group A was decompressed according to a U.S. Navy 210/50 schedule. Group B received an additional 3-min decompression stop at 70 fsw, which is 10 ft deeper than the initial stop on the 210/50 table (to make up for a too rapid ascent rate). The remainder of this decompression was in accordance with the original schedule and total decompression time was 3 min longer than normal for the 210/50 table. Group C was decompressed according to a 220/50 table. (During the initial compression the chamber was pressurized to 215 fsw for a period of 10 s before it was returned to 210 fsw; therefore, application of the next deeper table was required.) This table has 15 more minutes of decompression time distributed at the same depths as the standard 210/50 schedule. A comparison between the three schedules is shown in Table 1.

In the second series, 16 subjects were individually compressed to 132 fsw, using air as the initial breathing medium. At depth the breathing gas was changed to a normoxic nitrogen mixture for a TBT of 30 min. For approximately half of the bottom phase the divers exercised moderately in the upright position. The remainder of the time was spent undergoing psychological testing. Temperature and humidity were maintained within the comfort range for the subjects. There was no water immersion. At the end of this period 14 of the subjects (Group D) were decompressed using air according to a U.S. Navy 170/30 schedule, the equivalent air depth for this dive. The other two divers (Group E) received an extra 2-min decompression stop 10-fsw deeper than that required by the standard tables (see Table 1).

The completed, coded Doppler recordings obtained from both series were sent to the Institute of Applied Physiology and Medicine in Seattle, Washington, where a blind interpretation was made by associates who were not present during the actual experiments and who had no knowledge of the experimental protocols, the order or time sequence of recordings, or the dives from which the recordings were taken. The results were then returned to this facility and decoded. The scoring protocol (Spencer and Johanson 1974) can be found in Schedule 1.

Analysis of variance on bubble scores over time followed by tests of trends were performed for both dive series. Significance of the difference between group mean bubble scores over all time periods was computed by *t* test for individual comparisons for groups of unequal number (Winer 1962).

TABLE 1
Minutes of decompression at various depths for the five groups

Group*	Bottom time	Depths (fsw) 70	60	50	40	30	20	10	Total decompression time†
A	50	–	1	9	17	19	45	80	175
B	50	3	1	9	17	19	45	80	178
C	50	–	3	12	17	18	51	86	190
D	30					4	13	26	46
E	30				2	4	13	26	48

*Decompression schedules for each group are as follows:
Group A–210 normal
B–210 with extra stop
C–220 normal
D–170 normal
E–170 with extra stop
†Includes travel time

SCHEDULE I*

Zero	= No bubble signals.
GRADE I	= An occasional bubble signal. The great majority of cardiac cycles are free of bubble signals.
GRADE II	= Many but less than half of the cardiac cycles contain bubble signals.
GRADE III	= All of the cardiac cycles contain bubble signals, but not obscuring signals of cardiac motion.
GRADE IV	= Bubble signals sounding continuously throughout systole and diastole and obscuring normal cardiac signals.

*Modified from Spencer and Johanson (1974).

RESULTS

210-fsw dive series

Data from 17 man-dives are presented in Table 2; the data were collected from the 11 divers who were decompressed in a standard fashion (Group A), from those having an early deep stop (Group B, n=3), and from the group receiving 16 additional minutes of decompression time (Group C, n=3). No bubble signals (bubble score=0) were noted on any predive or bottom recordings.

A significant linear increase in bubble scores during the decompression stages monitored was noted. The linear trend (F_{lin}) for this series was calculated to be 54.43 ($P < .001$). This is represented graphically in Fig. 1. There was no statistically significant difference between bubble scores for Groups A and C (t=0.49, n.s.); however, a significantly lower bubble score overall for Group B than for Groups A and C combined (t=3.37, $P < .01$) was noted. The difference cannot be completely explained by the additional 3 min decompression time received by Group B divers because the divers in Group C had 15 additional minutes of decompression time and their bubble scores were not significantly different from the divers in Group A. Thus there is a statistically significant bubble-score reduction for those divers with the additional deep decompression stop that is not solely related to the additional decompression time. Some data (see Table 2) were not used in the above calculations since, due to technical errors, no control bubble scores were recorded prior to the dive. If these data are used the significance of the results increases.

132-fsw dive series

Data obtained from 14 divers are presented in Table 3. Part A represents the divers who were decompressed according to the standard 170/30 table (Group D, n=12). Data in Part B are from the divers who received the additional deep decompression stop (Group E, n=2). A comparison of these results is seen in Fig. 2. Again there was a statistically significant linear increase in bubble scores during decompression (F_{lin}=52.66, $P < .001$). The mean bubble score among divers who had a deeper decompression stop was again lower, but the level of significance was less than in the earlier series (t=1.91, $P < .10$).

During these two series of dives there were a total of five cases of decompression sickness. Two cases involved the central nervous system (see Table 3) and in three cases limb pain was the major symptom (see Table 2). Additionally there were two cases of cutaneous decompression sickness (bends) characterized by erythema, mottling, and purpura (see Table 2) and all of the subjects experienced itching, commonly referred to as *skin bends*. In all but one case the symptoms occurred within 1 hour of surfacing. In that case (S.W.) the symptoms occurred during the last minute of the 10-fsw decompression stop. All of the divers who experienced decompression sickness had Grade IV bubble scores during their last three recordings, whereas only 12 of the other 27 divers had similar bubble scores. The t test for the difference between these proportions was significant (t=2.30, $P < .05$).

There were no significant correlations between either age, weight, or ponderal index and the occurrence of either decompression sickness or mean bubble score.

TABLE 2

Bubble grades detected in individual divers at various stages of decompression for 210-fsw dives

Subject	Decompression stops at various depths (fsw)								Postsurface	
	50	40	30	20 (*early*)	20 (*late*)	10 (*early*)	10 (*late*)	*Surface*	15 *min*	30 *min*
				GROUP A 210/50 SCHEDULE						
HD	0	1	0	1-2	0	0	1	1-2	1	1
EJ	0	0	0	0	0	0	0	4	4	4
W[a]	1	2	4	4	4	4	4	4	4	4
DC	0	2	2-3	2	2-3	4	4	4	(4)	(4)
SW[b]	0	1-2	3	4	4	4	4	4	(4)	(4)
RC	0	0	0	0	2	4	4	4	4	4
NT[a, b]	0	0	0	2	1	3	4	4	4	4
OT[b]	0	0	2	2	4	4	4	4	4	(4)
K[c]	–	–	4	–	–	–	–	4	4	4
J[c]	–	–	4	–	–	–	–	4	4	4
SC[c]	–	–	4	–	–	–	–	4	4	4
				GROUP B 210/50 + EXTRA DEEP STOP						
MJ	0	0	0	0	0	0	0	0	0	0
SC	0	0	0	0	0	2-3	0	2	3	0
CA	0	0	1	1	1	4	0	2	2-3	1
				GROUP C 220/50						
CA	0	0	0	(2)	4	4	4	4	4	4
HS	1	1	2	2-3	4	4	4	4	4	4
PM	1	1	2	2	4	4	4	4	4	4

Compression time in all dives was 6 min ± 30 s. All predive and bottom bubble recordings were zero. Bubble scores in parentheses are interpolated and all between bubble grade classifications (1-2, 2-3, etc.) were given 0.5 for computation (1.5, 2.5, etc.).

a **Cutaneous bends.**

b **Limb bends.**

c **Partial data (not used in computation).**

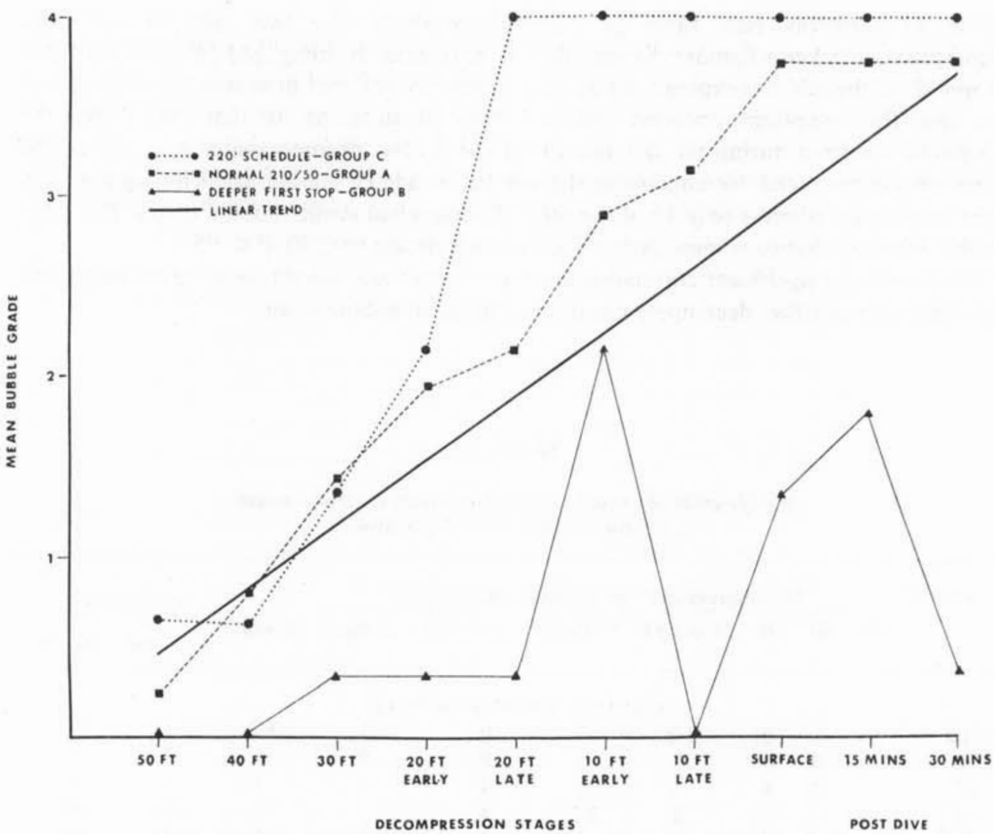

Fig. 1. Mean bubble grades during decompression and postdecompression for three groups following a 210-ft dive.

DISCUSSION

It was notable in this study that clinical decompression sickness only developed in those subjects with Grade IV bubble scores, monitored over three consecutive time periods. This strongly suggests a time-related, dose-response relationship between venous bubbles and decompression sickness. The dramatically lower bubble score associated with a slightly deeper first decompression stop also deserves comment. This clearly implies that deeper initial decompression stops allow markedly fewer venous bubbles to form. With fewer bubbles present initially there is apt to be less interference with ongoing inert gas elimination. Improved inert gas elimination should make subsequent decompression safer and possibly faster. This hypothesis is supported by the results of Kindwall, Baz, Lightfoot, Lanphier, and Seireg (1975), Fife, Mezzino, and Naylor (*in press*), and D'Aoust, Swanson, and Smith (1975).

Although the significance of our results in these small samples could be ascribed to chance individual variation, it is unlikely because of the replication in both series. It is also unlikely that bubble-resistant individuals had any significant bearing on the results since two of the three individuals in Group B (Subjects SC and CA, Table 1) made subsequent 210-fsw dives approximately 8 weeks later and had the high bubble scores observed in the other divers (Groups A and C). Acclimatization was not a factor since the divers in Group B were exposed to pressure first and at least 8 weeks elapsed between dives.

The results of these studies lead us to question the classic Haldane-ratio hypothesis. This hypothesis had accounted for the theory that all animals tolerate a much larger absolute-pressure reduction without decompression sickness if the initial ambient pressure is high. If the Haldanian ratio (i.e. final tissue pressure versus initial pressure) is not the critical factor, then one must discern what is. With the recent postulation that bubbles form during virtually any significant reduction in pressure (Hills 1970 a, b) and our demonstration that bubbles form in large numbers even during *safe* air-decompression procedures, the effects of pressure on these bubbles achieves greater and perhaps critical importance.

Bubbles formed at relatively high pressure would exert a smaller physiologic effect during decompression–since their growth rate is pressure-volume dependent–and, therefore, their size remains small as long as the ambient pressure remains high. Bubbles present at a lower absolute pressure would have larger volume changes associated with pressure reduction and thus could cause relatively greater physiologic effects.

One can hypothesize that bubbles form almost immediately during the initial ascent because, as we have shown, decompression during the deep phase is inadequate. This gas phase can then exert a continuously increasing effect as the diver proceeds to the surface,

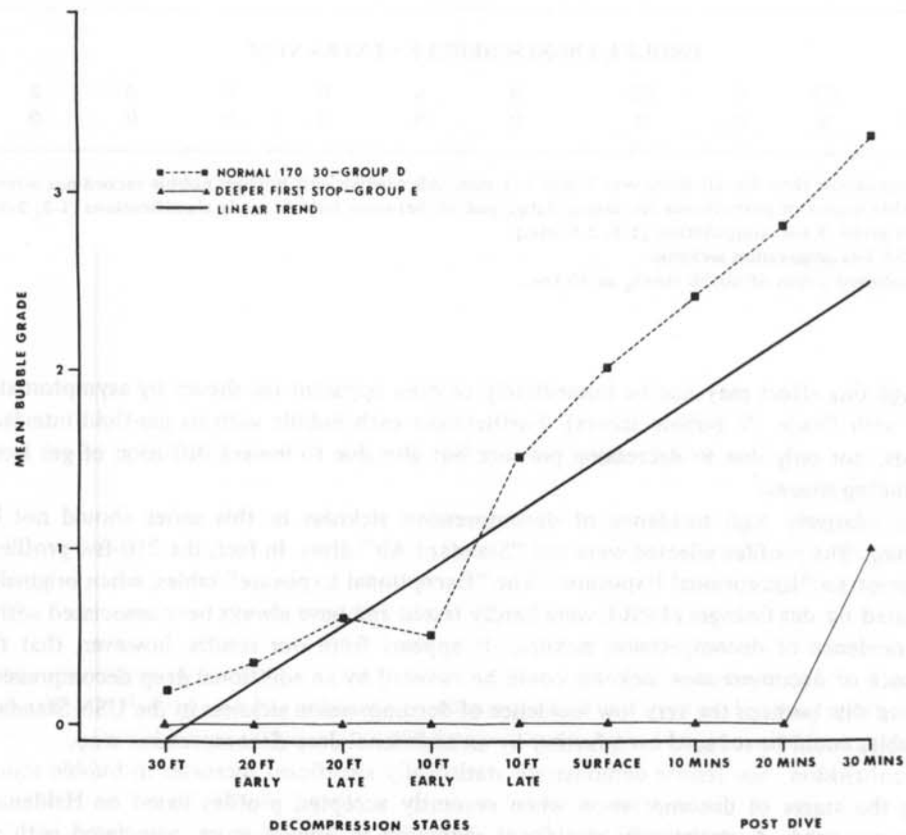

Fig. 2. Mean bubble grades during decompression and postdecompression for two groups following a 132-ft dive.

TABLE 3

Bubble grades detected in individual divers at various stages of decompression after 132-fsw dives

Subject	Decompression stops at various depths (fsw)					Surface	Postsurface		
	30	20 (*early*)	20 (*late*)	10 (*early*)	10 (*late*)		10 *min*	20 *min*	30 *min*
GROUP D 170/30 SCHEDULE									
SA	2	2	(2)	3	3	3	4	4	4
PM	0	0	0	0	0	0	1	1	1
CR[a]	0	0	0	0	4	4	4	4	4
HR	0	0	1	1	0	2	(3)	3-4	4
DF	0	0	0	0	2	1	1	(1-2)	2
CC	0	0	0	0	0	0	3	3	3
TJ	0	0	0	0	0	0	0	0	(0)
MU	(0)	(0)	(0)	(0)	0	0	0	0	2
C	0	0	1-2	1-2	2	3	4	4	4
OT	0	0	0	0	2	2	2-3	3	4
WJ[a, b]	0	2	2	0	3	3	4	4	4
D	0	0	0	0	0	0	0	3	3-4
GROUP E 170/30 SCHEDULE + EXTRA STOP									
PC	(0)	0	(0)	0	0	0	0	0	2
LE	0	0	0	0	0	0	0	0	0

Compression time for all dives was 4 min ± 1 min. All predive and bottom bubble recordings were zero. Bubble scores in parentheses are interpolated and all between bubble grade classifications (1-2, 2-3, etc.) were given .5 for computation (1.5, 2.5, etc.).

a CNS Decompression sickness

b Breathed 2 min of 80:20 He-O_2 at 10 fsw.

although this effect may not be immediately or even apparent (as shown by asymptomatic divers with Grade IV bubble scores). Furthermore each bubble with its gas-fluid interface expands, not only due to decreasing pressure but also due to inward diffusion of gas from surrounding tissues.

The relatively high incidence of decompression sickness in this series should not be surprising. The profiles selected were not "Standard Air" dives. In fact, the 210-fsw profile is considered an "Exceptional Exposure." The "Exceptional Exposure" tables, when originally calculated by des Granges (1956), were hardly tested and have always been associated with a high incidence of decompression sickness. It appears from our results, however, that the incidence of decompression sickness could be reduced by an additional deep decompression stop and that perhaps the very low incidence of decompression sickness in the USN Standard Air Tables could be reduced even further by an additional deep decompression stop.

In conclusion, our results demonstrate statistically significant increases in bubble scores during the stages of decompression when currently accepted profiles based on Haldanian theory are used. A statistically significant reduction in bubble score, associated with an additional deep decompression stop but unassociated with additional decompression time, was also observed. There was a statistically significant relationship between bubble score and decompression sickness. Further work with the Doppler bubble detector during routine diving operations– surface-supplied and saturation excursion– is indicated to supplement and amplify these results. Using bubble detection to monitor decompression could possibly lead to safer ways of calculating decompression tables.

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Reprints may be obtained from LCDR Tom Neuman, MC, USNR, Submarine Development Group ONE, Fleet Station Post Office, San Diego, California 92132. The opinions and assertions herein are those of the authors and are not to be construed as official views of the Navy Department, or the naval service at large.

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Neuman, T. S., D. A. Hall, P. G. Linaweaver, Jr. 1976. Séparation de la phase gazeuse an cours de la décompression chez l'homme: contrôle ultrasonique. Undersea Biomed. Res. 3(2):121-130.– Pendant deux séries de plongeés (à 132 fsw et à 210 fsw) des appareils de dépistage ultrasonique (effet Doppler) ont été utilisés pour étudier les bulles apparues chez les plongeurs pendant la décompression et les trente minutes suivantes. Plusieurs schémas de décompression ont été utilisés. Les taux de bulles ont été évalués par des écouteurs d'enrégistrements à double aveugle. Une augmentation significative des taux de bulles à travers les étapes de la décompression et de la période postdécompression a été mise en évidence, ainsi gu' une correlation statistiquement significative entre le taux de bulles et la maladie de décompression. Une chute du taux moyen de bulles a été constatée chez les plongeurs qui ont eu un étape supplémentaire pendant la décompression profonde, sans rapport avec la durée de la décompression. L'importance de ces résultats est discutée.

ultrasons
dépistage de bulles
maladie de décompression

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