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Relationship between pressure-reduction magnitude and stop time during stage decompression

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Berghage, T. E., G. S. Goehring, and C. V. Dyson. 1978. Relationship between pressure-reduction magnitude and stop time during stage decompression. Undersea Biomed. Res. 5(2):119–128.—Stage decompression was investigated to learn whether the amount of time spent at the first stop is independent of the magnitude of the initial pressure reduction. The effects of 3 different stop times (5, 40, and 120 min) and 5 different pressure reductions (3, 6, 9, 12, and 15 atm) were explored in a 3 × 5 factorial design using 375 female albino rats. A two-step, single-stage decompression was initiated after a saturation exposure at 30 ATA. The second step of the decompression was varied to establish a dose-response curve from which a 50% "bends" point could be extracted. Data analysis and subsequent inferences are based upon these ED_{50} points. Results suggest: 1) the greater the initial pressure reduction the smaller the possible subsequent pressure reduction; 2) the decompression stop time required to reestablish equilibrium after a pressure reduction is 10 times longer than that needed to reestablish equilibrium after compression; 3) there is an optimum decompression stop time that takes maximum advantage of the gas exchange rate; 4) short decompression stops are detrimental for further pressure reduction; and 5) a strong linear relationship exists between the optimum time spent at a decompression stop and the magnitude of the prior pressure reduction. If confirmed by large animal and human studies, these results could have a major impact on future decompression profiles.

decompression theory
rats

The use of stage decompression requires the ability to calculate two items: "step" size and stop time. In the past, each has been calculated as an independent item. The only interaction between step size and stop time has been through the supersaturation ratio associated with each tissue half time.

If an organism is at equilibrium with the surrounding environment, the decompression is controlled by a single tissue half time. In this situation the degree of tissue supersaturation controls the step size; the gas-exchange characteristics of the tissue control the stop time.

Many researchers have attempted to define the pressure-reduction limits for various exposure times (Boycott, Damant, and Haldane 1908; French 1916; Hawkins, Shilling, and Hansen 1935; Yarbrough 1937; Davidson, Sutton, and Taylor 1950; Van der Aue, Kellar, Brinton, Barron, Gilliam, and Jones 1951; Hempleman, Crocker, and Taylor 1952; Dwyer 1955; Des

Granges 1956; Workman 1965; and Spaur, Thalmann, Flynn, and Reedy 1976). Many of these researchers have developed procedures for calculating the time required at each decompression stage.

A recent attempt to develop a general model for calculating stage decompression is that of Workman (1965). The ascent control values for each tissue in this model are linear extensions of the individual surfacing values.

$$M = a + bx \qquad (1)$$

where M = maximum allowable tissue pressure; a = empirically derived surfacing values, fsw; b = empirically derived change in supersaturation associated with exposure pressure; and x = exposure pressure. The time to be spent at each stage of the decompression is determined by the following formula:

$$t = \frac{-H \ln\left(1 - \frac{M-P}{N-P}\right)}{\ln 2} \qquad (2)$$

where t = time at each decompression stage; H = tissue half time; N = partial pressure of inert gas in the breathing medium, fsw; M = maximum allowable tissue pressure, fsw; and P = initial tissue pressure at the start of any given time period, fsw.

Workman (1965) states that "at each decompression stop the controlling tissue determines the time interval for the stop. The controlling tissue pressure must fall to or below the maximum pressure allowable for that tissue at the next stop before all tissues may ascend to that stop." The calculation of step size and stop time are independent of each other if the organism is at equilibrium with the surrounding environment. This assumption of independence has never been tested experimentally.

In 1951 Bateman suggested that the time spent at each stage of the decompression is determined by both the desaturation time curve and the kinetics of growth and reabsorption of gas bubbles. In other words, the time course for elimination of gas is altered during decompression by the presence of free gas. If this is true, the time required at each decompression stage should be a function of the decompression step size rather than an independent entity.

This study concerns the relative independence of stage-decompression step size and stop time. Does the magnitude of the pressure reduction in any way affect the stop time required at each stage?

METHOD

Subjects were 375 female albino rats (NMRI:0[SD]CV, Sprague-Dawley derived). Mean and standard deviation free-feeding weight at the time of the experiment was 260.8 ± 30.2 g.

All pressure exposures were made in a Bethlehem Model 1836 10-HP chamber with a volume of approximately 170 liters. Chamber atmosphere was monitored with a Beckman Model F-3 paramagnetic oxygen analyzer; oxygen partial pressure was maintained at 0.51

ATA during the compression and time at maximum pressure. Carbon dioxide levels were checked and found to be 1% surface equivalent or less. Chamber pressure was monitored with a 0- to 1000-fsw Heise gauge and maintained within ± 2 fsw.

During each pressure exposure, five rats were exercised at a rate of 5 rpm (3.33 m/min) in a rotating cage. The 5-section cage, 63.5 cm long and 22.4 cm in diameter, is constructed of wire mesh over a Plexiglas frame. Each section is approximately 12 cm wide. The cage is rotated while in the chamber by a sparkless, shaded-pole motor (Eberback Corporation, Con Torque 115-V, 60-cycle 1/10-HP) (Berghage, Woolley, and Keating 1974).

The experimental procedure involved saturating the animals at 30 ATA.[1] After the 40-min exposure the animals were decompressed with a single stop to a point at which 50% of the animals displayed signs of decompression sickness. The combinations of initial pressure reduction and decompression stop time used in the study are shown in Table 1. Three additional conditions were added to the experimental design, which served as a check on the time course for gas elimination. One condition involved a 3-atm initial pressure reduction with a 240-min stop time; the second involved a 15-atm initial pressure reduction with a 240-min stop time; the third involved a 16-atm initial pull with a 120-min decompression stop. There was a total of 18

TABLE 1
EXPERIMENTAL DESIGN MATRIX

Time spent at decompression stop, min		Initial pressure reduction, atm 3	6	9	12	15
5	n	25	20	20	20	25
	r	0.96	0.95	0.98	0.99	0.90
	ΔPED_{50}	14.3	12.3	7.5	3.5	2.2
	Total	17.3	18.3	16.5	15.5	17.2
40	n	20	20	20	25	35
	r	0.98	0.99	0.96	0.88	0.52
	ΔPED_{50}	14.9	13.4	10.2	6.5	3.2
	Total	17.9	18.4	19.2	18.5	18.2
120	n	20	20	25	20	20
	r	0.95	0.99	0.95	0.99	0.94
	ΔPED_{50}	15.1	13.5	11.5	10.4	6.7
	Total	18.1	19.5	20.5	22.4	21.7

n = Number of rats used to establish ED_{50}; r = correlation coefficient for the ED_{50} best-fit line (least squares criterion); ΔPED_{50} = pressure reduction in atm that will produce decompression sickness in 50% of the animals. Total = sum of 1st and 2nd pressure decrements. *Note:* with no decompression stop, the ED_{50} pressure decrement is 18 atm (Berghage et al. 1976).

[1]Forty minutes have been found to produce an asymptotic level of decompression sickness for helium–oxygen exposures regardless of the exposure pressure (Berghage et al. *in press*).

conditions in the experimental design. The step-by-step procedure during the pressure exposures is provided below.

1. Compress to 10 fsw (1.3 ATA) with oxygen to establish the Po_2 at 0.51 ATA.
2. Compress to 957 fsw (30 ATA) with helium at the rate of 60 fpm (1.82 atm/min).
3. After reaching 30 ATA, check the oxygen percentage (1.7%) and make corrections as needed.
4. Remain at 30 ATA for 40 min.
5. Abruptly decompress 3, 6, 9, 12, or 15 atm after raising the Po_2 to 0.51 ATA for the pressure to which you are decompressing.
6. Check and adjust the oxygen level to obtain the appropriate percentage.
7. Remain at the decompression stop for 5, 40, or 120 min.
8. In the last 60 s of the decompression stop, ventilate the chamber to raise the Po_2 to 0.51 ATA for the pressure level you are approaching.
9. Decompress to the observation pressure level at the rate of 1 atm/s.
10. Remain at the observation pressure level for 30 min. At the end of this time the behavior of the animals is evaluated for presence or absence of decompression sickness. Signs of decompression sickness include paralysis, convulsions, and tumbling in the cage.

RESULTS

To obtain an initial evaluation of the experimental results, we conducted a simple analysis of variance of the results shown in Table 1, using the pressure reduction levels necessary to produce an ED_{50} as the dependent measure. The results appear in Table 2.

Figure 1 provides a graphical presentation of the statistically significant results shown in Table 2. The greater the initial pressure reduction, the smaller the subsequent pressure reduction needed to produce symptoms in 50% of the animals, if the time between the pressure reductions has been held constant. The relationship between the two pressure reductions appears to be linear; the correlations for each of the stop times are: 5 min, $r = -0.98$; 40 min, $r = -0.99$; and 120 min, $r = -0.98$. Two other points of importance can be obtained from this figure. The dashed line connecting the 18-atm points on the two axes is a theoretical relationship that assumes no time between the first and second pressure reduction. The value, 18 atm, is based on the previous study by Berghage, Gomez, Roa, and Everson (1976). Results for the 5-min decompression stops indicate that the animals could not decompress as far on the second pressure reduction as they could when there was no decompression stop. Only after the animals have at least 30 to 40 min at the decompression stop can they tolerate a subsequent pressure reduction equivalent to that for a no-decompression stop.

TABLE 2
ANALYSIS OF VARIANCE SUMMARY TABLE

Source	SS	df	MS	F	*P*
Stop time	30.29	2	15.15	8.43	0.01
Initial pressure change	232.58	4	58.15	32.35	0.001
Error	14.38	8	1.80	—	—
Total	277.24				

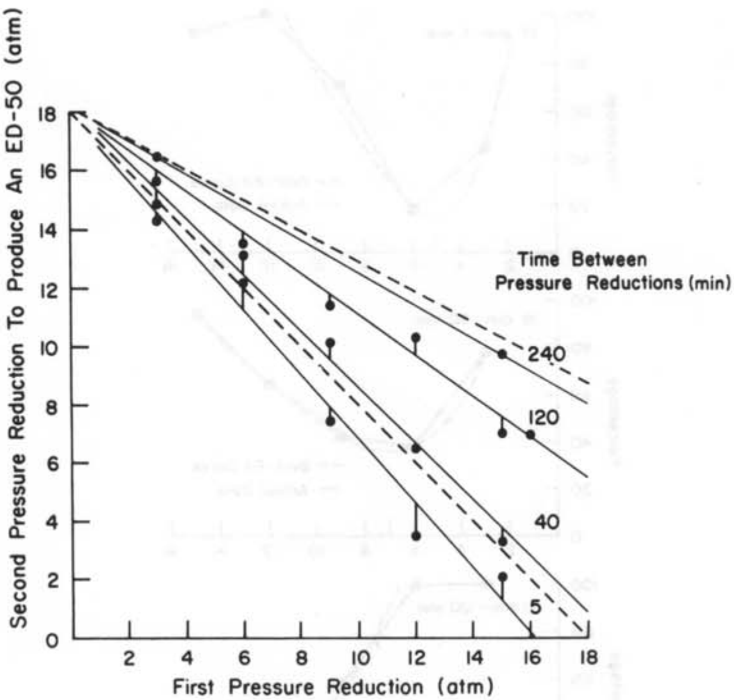

Fig. 1. Relationship of 2 pressure reductions separated by decompression stop of 5, 40, 120, or 240 min. Data points represent ED_{50}'s based on 20–25 rats. Lower dashed line represents ED_{50} pressure-reduction limits, assuming no decompression stop; upper dashed line represents ED_{50} pressure-reduction limits, assuming complete recovery from initial pressure drop.

The upper dashed line in Fig. 1 represents a theoretical ED_{50} relationship that assumes sufficient time was spent at the decompression stop to allow the animals to reestablish pressure equilibrium. The position of this line is again based on the work of Berghage et al. (1976).

The time required to move from the lower dashed line to upper dashed line in Fig. 1 is an indication of the time needed to reestablish equilibrium after a pressure reduction. Results suggest that it takes almost 300 min to transverse this distance or about 10 times longer to establish equilibrium after decompression than it takes to establish equilibrium after compression (Berghage, Goehring, and Donelson *in press*).

Figure 2 presents the same data in a slightly different form. Each graph shows the incidence of decompression sickness (DCS) for a given initial pressure change with stop time held constant. The top graph shows the DCS incidence after an intitial pressure reduction of 3, 6, 9, 12, and 15 atm with a 5-min decompression stop and a subsequent 14-, 11-, 8-, 5-, and 2-atm pressure reduction. In all cases the total pressure reduction, i.e., the sum of the first and second decompressions, is equal to 17 atm. The middle and bottom graphs are for decompression stops of 40 and 120 min, respectively. The total pressure reduction had to be changed in each case to keep the DCS incidence centered on the graph.

Figure 2 clearly indicates there is an optimum, initial pressure reduction for a given stop time, and vice versa: there is an optimum stop time for each pressure reduction level. The

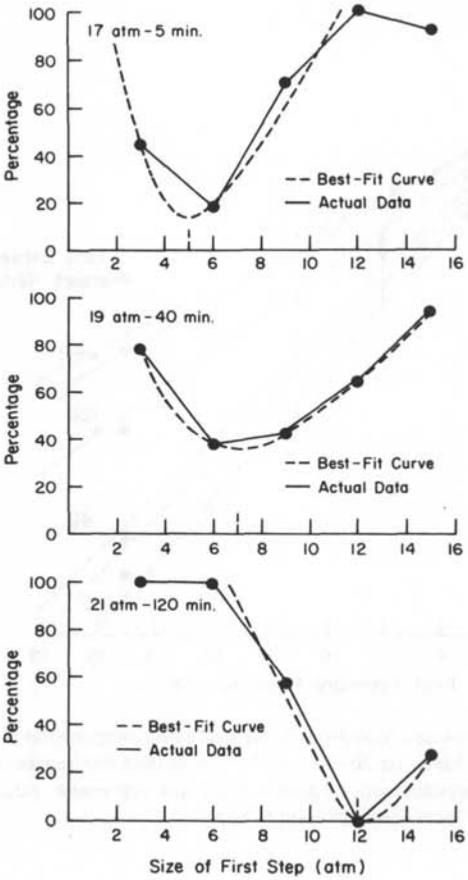

Fig. 2. Relationship between initial pressure reduction and the incidence of decompression sickness experienced on a subsequent pressure drop. Each graph represents a different time interval between pressure reductions; the atm pressure value in the body of each graph represents sum of the 2 pressure drops.

relationships between optimum pressure-reduction level and stop time can be described by Eq. 3.

$$y = 16.3x - 75.8 \tag{3}$$

where y = time in min; x = pressure change in atm; $r = 0.99$. As would be expected with only three data points, the strength of the relationship ($r = 0.99$) is impressive.

One final observation concerning the data in Fig. 1: if we look at the rate of change in body equilibrium occurring during the decompression stop, we get a plot similar to the one shown in Fig. 3. The rate of change (ROC) plotted in this figure is calculated from the data in Fig. 1 by the following formula:

$$\text{ROC} = \frac{\Delta P}{\Delta t} = \frac{\frac{P_2 - P_1}{2}}{\frac{t_2 - t_1}{2}} = \frac{P_2 - P_1}{t_2 - t_1} \quad (4)$$

where ΔP = change in pressure between observations; Δt = change in time between observations; P_1 = ED_{50} pressure reduction associated with the first stop time; P_2 = pressure reduction associated with the second time; t_1 = first stop time; and t_2 = second stop time.

The numerator is the change in ED_{50} pressure reduction between two observations. The denominator is the change in time between two observations.

The question of which time points along the *abscissa* of Fig. 3 should be used for plotting the ROC points was settled by using the following expression:

$$t_1 + \frac{t_2 - t_1}{2} \quad (5)$$

This produced a point midway between the stop times used.

Results suggest that for the first few minutes after a pressure reduction, the animals are actually at a disadvantage for subsequent decompression. They must stay at a decompression stop some fixed amount of time before their condition is sufficiently improved to continue decompression. It also appears there is an optimum stop time during which the animals experience the greatest rate of change. Beyond this optimum stop time, their condition continues to improve, but at a slower rate.

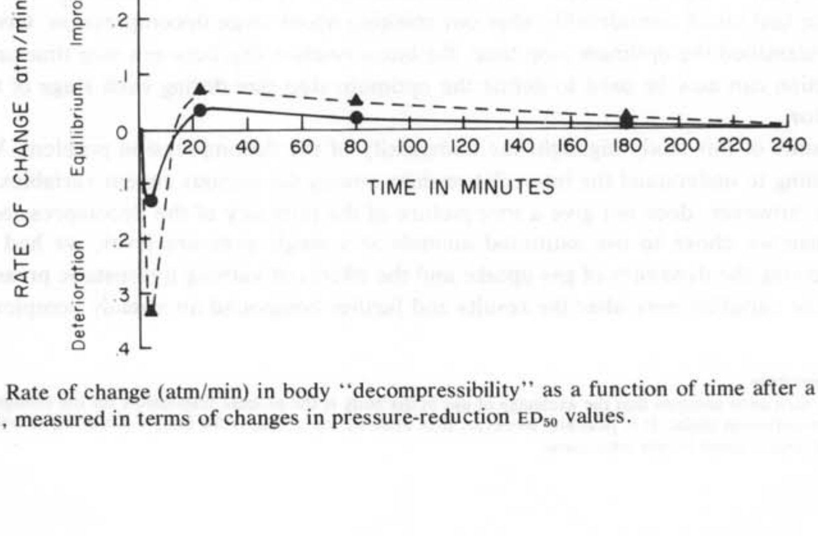

Fig. 3. Rate of change (atm/min) in body "decompressibility" as a function of time after a pressure reduction, measured in terms of changes in pressure-reduction ED_{50} values.

DISCUSSION

Three items of interest have been identified in this study. They relate to: 1) the time necessary to reestablish equilibrium after a reduction in pressure; 2) the existence of an optimum time to be spent at each decompression stop; and 3) the indication of a relationship between decompression stop time and the magnitude of pressure reduction between stops. All of these items could have a major impact on the decompression profile of the future.

The extended time required to reestablish equilibrium after a pressure reduction raises some serious questions concerning Haldane's assumption of symmetry between gas uptake and elimination. Our finding supports the work of D'Aoust, Smith, and Swanson (1976). The tenfold difference between equilibration after compression and that after decompression is certainly the largest difference so far reported. This may be attributed to the exposure pressure we were using or the animal species involved. D'Aoust et al. (1976) suggest that the difference may be the severity of decompression, which they term "the 'dose' of decompression stress sustained—a function of the total amount of gas dissolved and the relative decompression imposed." Results shown in Fig. 1 do not support this conclusion, because regardless of the magnitude of the initial pressure reduction, the time needed to reestablish equilibrium is about the same. The difference in time to equilibrium is about the same. The difference in time to equilibrium between compression and decompression may be a function of exposure pressure (total amount of gas dissolved), as suggested by D'Aoust et al. (1976).

The suggested time course for changes in body equilibrium shown in Fig. 3 is intriguing. It is difficult to accept the concept that divers who spend some minimal time at a decompression stop are in worse condition than if they had spent no time there. But there is support for this concept in the statistical literature. In 1968 Berghage presented a figure that indicated that the number of cases of bends that occurred on standard Navy air schedules with short-duration decompression stops was statistically higher than would be expected based upon their usage. The existence of this possible adverse effect from short-duration decompression stops should be explored.

Results depicted in Fig. 3 also indicate that there is an optimum time to spend at a decompression stop to experience the maximum rate of "body gas exchange." Staying longer at a decompression stop provides further improvement, but at a slower rate. If this observation is true, then the efficiency of a stage decompression could be improved by utilizing the optimum times associated with the maximum rate of gas exchange.[2]

The relationship between pressure-reduction level and decompression stop time is a powerful one that could considerably alter our thinking about stage decompression. Given that we have identified the optimum stop time, the linear relationship between stop time and pressure reduction can now be used to define the optimum step size during each stage of the decompression.

Results of this study highlight the complexity of the decompression problem. We are just beginning to understand the interrelationships among the various cogent variables. Even this study, however, does not give a true picture of the intricacy of the decompression problem. Because we chose to use saturated animals at a single pressure level, we had a problem concerning the dynamics of gas uptake and the effects of varying hydrostatic pressures. Both of these variables may alter the results and further compound an already complex problem.

[2]This statement assumes that the exchange of gas in the body is the process responsible for the changes in tolerable pressure-reduction limits. It is possible, however, that what we are seeing is the body's physiological response to the internal insult caused by gas separation.

It is conceivable that the time spent at stops during future stage decompressions could be a function of both the desaturation time curve and the kinetics of growth and reabsorption of gas bubbles, as Bateman (1951) originally suggested.

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The experiments reported herein were conducted according to the principles set forth in the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Resources, National Research Council, DHEW, Pub. No. (NIH) 74–23.

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Berghage, T. E., G. S. Goehring, and C. V. Dyson. 1978. Rapport entre la réduction de pression et la durée de l'arrêt au cours de la décompression par étapes. Undersea Biomed. Res. 5(2):119–128.—Nous avons étudié la décompression par étapes pour évaluer les effets de la durée du premier arrêt sur la réduction initiale de la pression. Les effets de trois durées d'arrêt (5, 40, et 120 min) et de 5 réductions de pression (3, 6, 9, 12, et 15 atm) ont été explorés par le moyen d'un schéma factoriel dont les sujets étaient 375 rattes albinos. La décompression en deux périodes, avec un seul arrêt, a suivi la compression à saturation à 30 ATA. Nous avons varié la deuxième période de la décompression pour établir une courbe de dose-résponse de laquelle nous avons pu calculer un point de "50% maladie de caisson" (ED_{50}). L'analyse des résultats et les déductions qui s'ensuivent se basent sur ces points de ED_{50}. Nous concluons que: a) la réduction subséquente de pression est d'autant plus modeste que la réduction initiale était grande; b) la durée d'arrêt nécessaire pour rétablir l'équilibre après une réduction de pression est dix fois plus longue que celle nécessaire pour rétablir l'équilibre après la compression; c) il existe une durée d'arrêt optimum où le rapport d'échange grazeux est le plus avantageux; d) des arrêts brefs font obstacle à la réduction de pression continue; et e) il existe un rapport linéaire entre la durée optimale d'un arrêt et la réduction antérieure de pression. Si des études plus étendues confirment nos résultats, ils changeront profondément les schémas de décompression futurs.

théorie de décompression
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