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TITLE

EXERCISE DURING DECOMPRESSION REDUCES THE AMOUNT OF VENOUS GAS EMBOLI

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Exercise during decompression reduces the amount of venous gas emboli

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Jankowski LW, Nishi RY, Eaton DJ, Griffin AP. Exercise during decompression reduces the amount of venous gas emboli. Undersea Hyperbaric Med 1997; 24(2):59–65.—To determine the effects of moderate, intermittent exercise during decompression on the Doppler detectable amount of venous gas emboli (VGE), 29 healthy male volunteers performed 44 wet (8° ± 2°C) dives to 45 msw (450 kPa) for 30 min with standard air decompression. During compression and the bottom period, all subjects were inactive; during decompression, 28 remained inactive, 11 performed leg exercise, and 5 did arm exercise. Intermittent exercise was controlled at approximately 50% of each subject's arm or leg aerobic capacity. At 30-min intervals after surfacing, subjects were monitored with a Doppler ultrasonic bubble detector. The Doppler scores were used to calculate the Kisman Integrated Severity Score (KISS). The KISS were log transformed (with zeroes being equivalent to log 0.01) and analyzed with a one-way analysis of variance. No significant differences ($P \leq .05$) between mean KISS scores after arm or leg exercise were observed, thus these data were pooled and compared to those of the inactive controls. The mean pooled KISS after exercising during decompression were significantly lower than those of the inactive controls. Moderate, intermittent exercise during decompression apparently reduces the amount of Doppler-detectable VGE after diving. The incidence rate of decompression sickness in both groups was not significantly different ($P < 0.05$).

Doppler, decompression sickness, venous gas emboli, bubbles, decompression, hyperbaric, diving

Exercise before, during, and after diving is associated with an increased risk of decompression sickness (DCS) (1–5). Vann and Thalmann (1) have produced elegant and comprehensive theses on the relation between exercise and the risk of DCS. In summary, the risk of DCS is related to both the exercise intensity and the phase of the dive during which exercise is performed. Vigorous or ballistic exercise, to the point of muscle soreness, before diving may create gas nuclei which increase the risk of DCS after diving. Exercise during diving increases inert gas absorption and the subsequent risk of DCS (2). Exercise on the surface after diving may cause cavitation, increase bubble formation and precipitate the coalescence of existing microbubbles, which combine to increase the risk of DCS (1,2,4,5). Exercise during decompression, however, apparently facilitates inert gas elimination and may actually reduce the risk of decompression sickness after diving (3, 4,6).

Indeed, Boycott et al. (6) recommended in 1908 that divers and caisson workers exercise during stage decompression. They had observed that small animals with high metabolic rates displayed no obvious effects after decompression experiments that were "invariably fatal in goats" (6:356). They postulated that: "a rapid circulation of the tissues facilitated inert gas transport during both saturation and desaturation . . . phases of diving." Consequently, they advocated that divers and caisson workers increase their metabolic rates during stage decompression by constantly moving their arms and legs (6:367). Subsequent research on the benefits of exercising during decompression has been surprisingly limited. This scarcity of research seems related to the notion that exercise during decompression is dangerous because it may increase the risk of DCS. This belief apparently originated in the title of a 1949 U.S. Navy research project report (5). The authors observed a 34% increase in the incidence of DCS among divers who lifted light weights "topside" for approximately 2 h after performing single no-decompression dives to 40, 100, and 120 feet of seawater (122, 306, and 368 kPa, respectively). Although the weightlifting exercise was performed after no-decompression diving, the report was entitled: "The effect of exercise *during* decompression from increased barometric pressures on the incidence of decompression sickness in man."

Schibli and Bühlmann (7) and Bühlmann (8) studied the influence of work on decompression time for helium–oxygen dives. They established that, compared to resting dives, work performed during the bottom phase of a dive

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increased the decompression time required to prevent DCS (defined as pains in muscles and joints). Work during the bottom phase increased minimum decompression time by 44% for dives at 90 meters of seawater (msw) (900 kPa) for 60 min, 19% for 90 msw for 120 min, and 20% for 35 msw (350 kPa) for 180 min. They also studied the hypothesis that work during decompression reduced the rate of DCS. They observed no increase in the incidence of DCS after 22 dives to 90 msw for 60 min and 18 dives to 35 msw for 180 min when subjects exercised during the final phases of the decompression after working during the bottom phase. However, they preferred to prolong the decompression time so that it was adequate for the time worked on the bottom and did not investigate the hypothesis that exercise during decompression would reduce minimum decompression times. Consequently, little can be determined from this experiment regarding the influence of work during decompression except that it does not seem to increase the incidence of DCS.

To investigate the hypothesis that exercise may increase the rate of inert gas absorption, Dick et al. (3) used a closed-circuit technique to measure the pulmonary nitrogen discharge of divers after no-decompression dives during which subjects either rested or exercised. During the 1st h on the surface, the expired nitrogen volumes of divers who had exercised were significantly (20–64%) greater than those of the divers who had not exercised. Radermacher et al. (9) investigated the effects of exercising on the surface after diving. They studied five subjects after no-decompression dives to 3 atm abs (304 kPa) for 20 min and reported that 30 min of mild exercise significantly increased blood nitrogen content ($P\bar{v}_{N_2}$) and accelerated the rate of nitrogen elimination but did not stimulate bubble formation nor DCS symptoms. Low intensity exercise after diving may accelerate inert gas elimination but does not invariably precipitate the formation of intravascular gas bubbles (9).

The purpose of this investigation was to determine the effects of moderate, intermittent exercise during decompression on the Doppler-detected intravascular gas emboli recorded after diving.

MATERIALS AND METHODS

These experiments were approved by the Human Research Ethics Committee of the Defence and Civil Institute of Environmental Medicine (DCIEM), Department of National Defence, Canada, and conducted in the water-filled (8° ± 2°C) portion of the DCIEM Diving Research Facility's hyperbaric chamber. Twenty-nine healthy adult males, 10 professional divers serving in the Canadian Armed Forces and 19 commercial diving students from the Seneca College Underwater Skills Program, volunteered to participate in this study. All subjects gave their written informed consent after a full-disclosure orientation, as prescribed by the DCIEM Human Research Ethics Committee, and voluntarily performed a total of 44 air dives at a maximal pressure equivalent to 45 msw (450 kPa) for 30 min, followed by a 55-min staged decompression according to the DCIEM Standard Air Diving Table (10,11). Some divers elected to make a 30 msw (300 kPa) 12-min no-decompression "work-up" dive no less than 2 days before their first experimental exposure. A minimum of 36 h was required between the start of two consecutive experimental dives for any subject. The military divers generally had 2 days between dives whereas the commercial diving students had 1 wk between consecutive dives.

Procedure

All volunteers were examined by a diving medical specialist who certified they were fit to participate in this investigation. Participants were instructed to avoid strenuous physical activity, weight training, and alcohol for 24 h before each experimental dive. Approximately 1 h before each experimental dive, the subjects were confirmed fit to dive.

Preliminary exercise testing: Before beginning the hyperbaric experiment, the physical work capacity of each subject for both arm and leg exercise was measured during two separate standardized, progressive, physical work-capacity test protocols performed on two separate occasions approximately 1 wk apart. Leg exercise was performed on a mechanically braked bicycle ergometer (Monark) while arm exercise was performed by cranking a modified bicycle ergometer (Monark) adapted for arm work with a pediatric resistance scale. The rate of oxygen consumption ($\dot{V}O_2$) measured continuously with a metabolic cart (Sensormedics 4000 Mobile Metabolic Laboratory, Sensormedics, CA) and each subject's heart rate, monitored continuously, were used to determine the $\dot{V}O_2$–heart rate relationship for both arm and leg exercise for each subject. As is illustrated in the example shown in Fig. 1, these data provided a convenient method of calculating a target heart rate which was equivalent to approximately 50% of each subject's arm or leg aerobic capacity. This heart rate was used to control the intensity of underwater exercise.

Experimental protocol: During the experiment, divers wore a well-fitting, 7-mm neoprene dry suit, a 19-oz fleece undergarment (Pajesga), and 3-mm three-finger neoprene mitts. The exercising divers breathed surface-supplied compressed air using diving helmets (Superlite 17B, Diving Systems International, CA), while the sedentary, standby divers wore a 3-mm neoprene hood and breathed

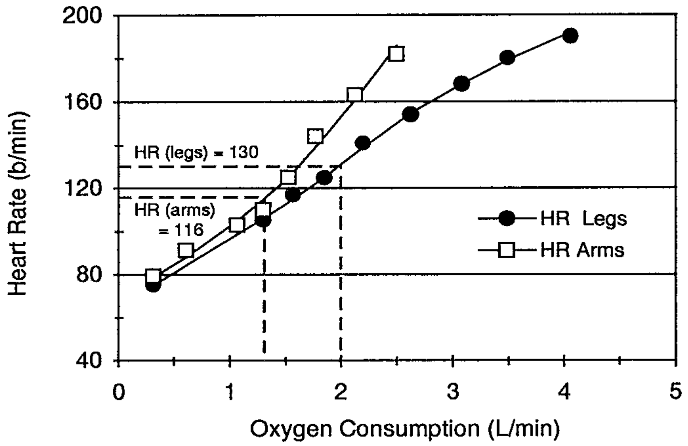

FIG. 1—Example of the oxygen consumption/heart rate relationship used to calculate target HR for submerged arm and leg exercise.

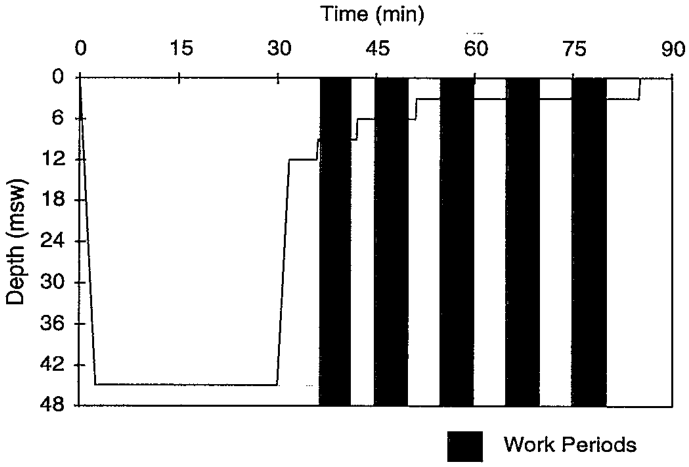

FIG. 2—Dive profile to 45 msw (450 kPa) for 30 min, showing exercise periods.

from a full face mask (Divator II (AGA) Interspiro, Sweden) while sitting immersed to the neck between the double barriers of the Lanphier–Morin-type chamber (12).

While each participant continuously indicated that they were comfortable and willing to continue the experiment, the hyperbaric chamber was pressurized at 18 msw/min (180 kPa/min) until the pressure reached 45 msw (450 kPa). All divers remained inactive during the compression and bottom phases of the dive (Fig. 2). Thirty minutes after the start of the dive, the pressure within the chamber was reduced at the rate of 18 msw/min with decompression stops as illustrated in Fig. 2. Decompression was accomplished by following stops prescribed by the DCIEM air diving model running on an on-line, real-time dive computer (IBM-compatible 386 DX40, Lab Windows data acquisition software and hardware, National Instruments, Austin, TX).

Beginning at minutes 7, 15, 25, 35, and 45 of the 55-min decompression period, randomly selected subjects performed intermittent 5-min periods of moderate arm or leg exercise. Each 5-min exercise period was followed by a 5-min rest in a sitting position. Eleven subjects performed leg exercise while five performed arm exercise. Leg exercise was performed on submersible, electromagnetically braked bicycle ergometers (Warren E. Collins, Braintree, MA) installed in the dive chamber. The ergometers were waterproofed in the manner described by Thalmann et al. (12). Arm exercise was performed on a custom-built paddle ergometer or by lifting light weights. The intensity of underwater exercise was controlled by monitoring the subject's heart rates (13,14) via unorthodox precordial electrocardiograph leads hard-wired through the dive chamber to electrocardiograph recorders equipped with digital cardiotachometers (MultiCare Model 304, Rigel Research Ltd., Morden, Surrey, England). No attempt was made to correct the heart rates for the possible effects of immersion or elevated Po_2. During these experiments, 16 stand-by (safety) divers performed a total of 28 control dives by remaining inactive during both the dive and the decompression.

Intravascular bubble monitoring: Within 30 min of ending the experimental dive and at 30-min intervals thereafter for the next 90 min, the amount of venous gas emboli (VGE) in each subject was determined (15) a total of 4 times by one of two experienced technicians using Doppler ultrasonic bubble detectors (TSI DBM 9008, Techno-Scientific Inc., Woodbridge, Ont). (Individuals with high Doppler scores were monitored until the scores decreased and they were released by the Diving Medical Officer. These additional data were excluded from analysis.) Subjects' precordial regions and their left and right subclavian veins were monitored with the subject at rest and after muscle flexion during a specific movement (deep knee bend for precordial and clenching of the ipsilateral fist for the left and right subclavian veins). During this procedure, the audio output from the bubble detector was manually scored using the Kisman-Masurel (KM) code (15–17) while being recorded on audio cassettes. The KM code uses three digits ranging from 000 to 444 which provide a relative rating for the frequency of bubbles per cardiac cycle, the percentage of cardiac cycles with bubbles during the resting condition (or the duration, i.e., number of cardiac cycles of elevated bubble signals, after muscle flexion), and the amplitude of the bubble signal relative to the blood flow signal. The KM code, converted to an equivalent ordinal bubble grade from 0 to IV (0, I–, I, I+, II–, ..., III+, IV–, IV), was then used to calculate the Kisman Integrated Severity Score (KISS) according to the following formula (18,19):

$$KISS = [100/4^{\alpha}(t_4-t_1)]x[(t_2-t_1)(d_2^{\alpha}+d_1^{\alpha}) +(t_3-t_2)(d_3^{\alpha}+d_2^{\alpha}) +(t_4-t_3)(d_4^{\alpha}+d_3^{\alpha})]/2$$

where

$\alpha = 3$

t_i = time of observation in minutes after reaching surface

d_i = Doppler score (grades 0 to IV) observed at time t_i.

The parameter, **α**, takes into account that the bubble grade is not a linear measure of bubble quantity (+, – Doppler scores were treated by adding or subtracting 0.3, respectively, from the Doppler scores). Doppler scores are often reported using the single maximum bubble grade observed for a subject. This method unfortunately does not distinguish between a diver with a single grade III KM score during four observations (III,0,0,0) conducted over 2 h (KISS = 7.0), and another diver with four grade III KM scores (KISS = 42.2) during the same period. KISS reveals and quantifies this difference by integrating the bubble scores over time. The KISS was assumed to be a meaningful, linearized measure of post-decompression intravascular bubble activity status (19) which may be treated statistically and was used in this investigation to determine the effect of moderate intermittent exercise during decompression.

RESULTS

The physical characteristics of the subjects, their diving background, the experimental protocols they performed, and the incidence of DCS are presented in Table 1. Although the control group was significantly older than the exercise group, there was no observable correlation between age and KM scores among the control group. In fact, the older controls' KISS tended to be lower than those of the younger controls. One definite case of DCS was diagnosed in the control group. This subject was treated before completion of the Doppler monitoring period; as a result, this data could not be used to calculate the KISS. In the exercise group, two definite cases of DCS were diagnosed and treated. Although another subject in this group was treated, it was subsequently determined that the symptoms were not related to DCS. All three cases in the exercise group were treated after the Doppler monitoring period was completed; hence, their data have been used in the analysis.

The mean KISS and their respective standard errors for the precordial, left and right subclavian sites, at rest and after a single muscle contraction, are presented in Table 2. Table 2 compares the mean ± standard error of the severity scores of the 16 controls who performed a total of 28 experimental dives followed by inactive decompression with the 5 subjects who performed intermittent moderate arm exercise as well as 11 subjects who did intermittent moderate leg exercise during decompression. Since the mean KISS after both arm and leg exercise were similar and not significantly different from each other ($P > 0.05$), the data for arm and leg exercise were pooled to form a single exercise group for analysis.

Doppler monitoring was unable to detect VGE in 57.3% of the exercise group and 22.6% of the inactive controls. Consequently, the KISS data failed to satisfy the criteria of a homogeneity of variance test. The KISS data were therefore log transformed (20), with KISS = 0 as equivalent to log 0.01, and then analyzed with a one-way analysis of variance procedure followed by a Tukey's Studentized range test with alpha = 0.05. The statistical analyses were performed using version 6.03 SAS/STAT Statistical Package (20). The mean KISS at rest and after movement, at all three sites, were significantly lower than control values after moderate-intensity, intermittent exercise was performed during decompression.

DISCUSSION

The hypothesis that mild exercise during decompression decreases Doppler-detected VGE is supported by the results. The intended eventual purpose of this investigation was to determine if the intervention of performing mild exercise during decompression decreased the risk of decompression or could alternatively be used to decrease decompression time. However, an investigation of this sort, based on a binary outcome of DCS vs. no DCS, would come at a high cost. For example, to test the hypothesis that exercise during decompression would decrease the risk of DCS from 5 to 2%, 1,228 dives, half with exercise during decompression and half without, would be required. Fewer tests could be done by accepting 5% as a standard so that testing for a decrease to 2% would require only 307 dives with exercise during decompression to test the hypothesis. Clearly, an experiment of this magnitude should not be undertaken without preliminary evidence that the hypothesis is supportable. Doppler ultrasonic monitoring of VGE in this experiment provided evidence that circulating VGE are reduced by mild exercise during decompression. The amount of circulating VGE seems to be an important element in the consideration and comprehension of the complex influence of exercise on the incidence of DCS.

Doppler ultrasonic monitoring of circulating intravascular bubbles is recognized as a valid, practical, and safe alternative to provoking DCS for research purposes

Table 1: Physical Description of the Experimental Subjects

Subject Number	Age, yr	Ht, cm	Wt, kg	$\Sigma_4 S\psi$, mm	Diving Background	Type of Exercise	Number of Dives	DCS
Group A: Inactive during decompression								
2	35	190	86	62	military	0	1	0
3	24	175	85.5	84	student	0	1	0
4	29	173	90.5	92	military	0	1	0 (treated)
6	31	183	91	71	military	0	5	0
7	40	180	83	70	military	0	1	0
8	22	184	81	64	student	0	1	type 1
9	37	175	78	64	military	0	1	0
12	40	169	73	86	military	0	2	0 (?)
14	20	178	81	88	student	0	1	0
17	29	185	81	39	student	0	3	0
19	30	177	73.5	48	military	0	3	0
21	20	175	94	117	student	0	1	0
22	34	182	76	52	military	0	4	0
23	40	170	81	74	military	0	1	0
25	23	178	62	40	student	0	1	0 (?)
28	21	190	68	32	student	0	1	0
Mean	29.7	179.0	80.3	67.7				
SE	1.9	1.6	2.1	5.6				
SD	7.4	6.3	8.5	22.6				
Group B: Exercise during decompression								
1	23	171	71	51	student	arm	1	0
4	29	173	90.5	92	military	leg	1	0
5	23	175	79	40	student	leg	1	type 1
10	26	188	86	49	student	arm	1	0
11	26	182	81	53	student	leg	1	0
13	23	177	78	70	student	arm	1	0
14	20	178	81	88	student	leg	1	0
15	20	175	44.5	44.5	student	leg	1	0
16	21	179	91	89	student	leg	1	type 1
18	33	174	82	56	military	leg	1	0
20	30	185	94.5	103	student	leg	1	0
24	22	173	67	58	student	leg	1	0
26	25	178	69	52	student	arm	1	0
27	25	193	97	60	student	leg	1	0
28	21	190	68	32	student	arm	1	0
29	20	176	67	61	student	leg	1	0
Mean	24.2*	179.2	62.4					
SE	1.0	1.6	5.1					
SD	3.9	3.9	20.4					

*Statistically significant from control mean: $t_{(\text{one tail})} = 2.63$; $P = 0.007$; ψ sum of triceps, biceps, and subscapular and suprailliac skinfolds; ? questionable but not treated. Note: Data from subject 8 was not used because the diver was monitored only twice for bubbles before being treated for recompression.

(17,21,22). Doppler bubble scores provide a risk assessment for an entire sample of divers which may be used to compare the severity of different dive profiles in groups of asymptomatic divers. However, the Doppler method detects only circulating intravascular bubbles whereas stationary bubbles, which are thought to cause DCS symptoms (23,24), may reside within various tissues and remain undetectable. Conversely, the VGE detected during Doppler monitoring are not thought to cause DCS (24). Rather than studying the incidence and severity of subjective symptoms of DCS, the Doppler procedure produces useful data from every dive exposure and provides a

Table 2: Mean and Standard Errors of the KISS for Inactive Decompression and Moderate Arm or Leg Exercise During Decompression

	PCR	PCM	LSR	LSM	PSR	RSM
Inactive, n = 28						
Mean	14.4	27.6	9.4	9.2	14.2	26.2
SE	3.1	5.2	3.1	5.1	3.2	5.6
Leg exercise, n -= 11						
Mean	7.0	10.6	2.4	3.2	0.4	1.1
SE	3.6	5.2	1.4	2.7	0.2	0.7
Arm exercise, n = 5						
Mean	6.0	10.1	0.1	0.1	0.2	1.2
SE	4.1	6.7	0.1	0.1	0.1	0.9
Exercise pooled, n = 16						
Mean	6.7[a]	10.4[a]	1.6[a]	2.2[a]	0.3[a]	1.1[a]
SE	2.8	4.1	1.0	1.9	0.1	0.6
Percent control value	46.5	37.7	17.0	11.4	0.2	4.2

Key to Doppler monitoring sites and conditions: PC = precordial, LS = left subclavian, RS = right subclavian, R = at rest, M = after muscular contraction.

[a] Denotes a significant difference from the control value at $P \leq 0.05$. Data gathered every 30 min for 2 h after 44 dives to 45 msw/30 min.

means of estimating the overall risk of DCS (17). Although very high Doppler scores are associated with a significant probability of developing DCS (17,21,24) and low bubble scores are infrequently associated with DCS (17,18,21,22), the overall correlation between Doppler scores and the incidence of DCS is inconsistent (22). Since Doppler scores cannot determine or predict the individual risk of DCS after a specific dive, they have no value as diagnostic or prognostic indicators in individual cases. For these reasons, simply comparing Doppler scores and observed DCS incidence rates has been inconclusive.

This study was not designed to examine incidence of DCS. Nevertheless, the occurrence of DCS (1 case in 28 control subjects vs. 2 cases in 16 exercising subjects) cannot be disregarded. A comparison of the two groups, using Fisher's exact probability test, yields a probability value of $P = 0.54$, which is interpreted as illustrating the insensitivity of this experimental design to DCS incidence. Furthermore, the 95% confidence intervals overlap, i.e., 0.2–17% for the control group and 2.3–35% for the exercising group. Consequently, the only conclusion about DCS which may be drawn from these results is that the incidence in both control and exercise conditions overlap the 95% confidence limits associated with the estimated risk of DCS in the DCIEM Standard Air Table (11,25). It is possible that even moderate exercise during decompression increases the risk of DCS. Since both the rapid elimination of inert gas and enhanced bubble growth, through some yet undefined mechanism triggered by exercise, may not be mutually exclusive, the intensity of exercise during decompression seems to be a critical parameter which requires additional investigation.

The analysis of Doppler scores using the KISS is a valid and objective means of determining a group's post-dive acute, intravascular bubble status. A high mean KISS indicates a large quantity of detectable intravascular bubbles which is associated with an increased risk of DCS, whereas a low mean KISS is indicative of a small quantity of detectable bubbles and a low risk of DCS (17). The resting precordial KISS after exercising during decompression, for example, were 46.5% lower than control values (Table 2). Since the exercise group KISS values were consistently lower than those of the inactive controls, moderate intermittent exercise during decompression apparently facilitated inert gas elimination and reduced the detectable quantity of VGE.

The observation that exercise during decompression may facilitate inert gas elimination, thus reducing the quantity of VGE, is consistent with the classic studies of Boycott et al. (6), the Schibli and Bühlmann report (7), several investigations reported by Vann and colleagues (1–4), and the report of Radermacher et al. (9). Moderate physical exercise increases rate of oxygen consumption which necessitates an increased minute ventilation and a concomitant increase in cardiac output. The increased cardiac output is associated with peripheral vasodilation, the enhanced perfusion of active muscles, and a simultaneous increased pulmonary perfusion. These increases in the tissue and pulmonary perfusion rates would facilitate the elimination of inert gas from tissue regions with high inert gas partial pressures to the lungs, where comparatively low inert gas partial pressure would be maintained by the increased alveolar ventilation due to exercise hyperpnea. This explanation may be particularly well suited to the results of this investigation since the specific effects of either arm or leg exercise were of no obvious importance, and the observed effect of a moderate increase in metabolism on the rate of inert gas elimination was apparently independent of the particular limbs used or the muscles exercised. The possibility that exercise may have increased the amount of VGE during decompression was not investigated because the exercising subjects were immersed and could not be Doppler monitored with the equipment used.

In conclusion, KISS have been used to determine that intermittent moderate exercise during decompression significantly reduces the amount of Doppler-detectable intravascular gas emboli compared to traditional inactive decompression procedures. It remains to be determined if moderate exercise during decompression can reduce the incidence of DCS and if exercise may be used to reduce the duration of decompression while maintaining or enhancing diver safety.

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