Altitude Decompression Sickness Risk and Physical Activity During Exposure

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INTRODUCTION: Earlier research described a linear relationship between the highest 1 min of oxygen consumption ($\dot{V}O_2$) during a recurring physical activity and incidence of decompression sickness (DCS) during research chamber exposures to high altitude. The current effort was designed to determine if that relationship holds true at a lower altitude.

METHODS: Male subjects (20) were exposed without prebreathe to 22,500 ft (6858 m; 314 mmHg; 6.1 psi) for 4 h while seated, nonambulatory the entire time, with echo-imaging at 16-min intervals (Non-Amb Echo), breathing 100% oxygen. Average highest 1 min of $\dot{V}O_2$ and level of activity was determined. Results during Non-Amb Echo were compared with earlier research data acquired under identical conditions except for higher levels of activity.

RESULTS: No DCS was reported or observed and no venous gas emboli were observed. Combined with earlier data, a strong linear relationship ($r > 0.99$) was observed between DCS incidence and level of activity.

DISCUSSION: These results suggest physiological envelopes might be expanded or prebreathe time reduced for some high-altitude aircraft operations that involve very low levels of physical activity. They may also help to explain the higher DCS risk for inside observers vs. trainees during altitude chamber training. The data imply potential for update of altitude DCS risk prediction models by adjustment with quantified level of activity during exposure.

KEYWORDS: decompression sickness, altitude, oxygen consumption, human.

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The literature regarding effects of exercise on incidence of altitude decompression sickness (DCS) is extensive, and results indicate the timing and extent of the physical activity is crucial.[4,8] Exercise before, during, and after decompression have very different effects.[5,9,10] When exercise is performed prior to decompression while breathing 100% oxygen,[29] it is evident that the increased perfusion and ventilation provides significant risk mitigation.[2,12,30] Exercise after recompression from exposure to an altitude associated with a high risk of DCS has been shown to have no effect on DCS risk.[34] However, activity and/or exercise while decompressed can significantly increase the level of altitude DCS risk.[7,14]

Reviews of the effects of exercise during exposure to reduced pressure support the concept that exercise intensity is directly proportional to resulting levels of DCS.[15,18,22] Although not quantified, many reports described exercise at altitude as increasing the incidence and/or reducing the onset time or altitude of occurrence.[21,25,27] A high association between incidence of incapacitating symptoms of DCS and foot pounds of work performed at 38,000 ft (11,582 m; 155 mmHg, 3.0 psi) was reported by Henry.[13] Gray & Masland[11] found that exercise at altitude increased the percent of descents due to symptoms and lowered the altitude threshold for incidence of symptoms requiring descents from 32,000 ft (9754 m; 206 mmHg, 4 psi) to 23,000 ft (7010 m; 307 mmHg, 6 psi).

The relationship between exercise and bubble formation was discussed by Ikels[16] during a study of bubble formation in olive oil by tribonucleation during relatively moderate decreases in barometric pressure. He stated that articulating surfaces of joints where synovial fluid may display a high viscosity were similar to the model tested during his study in which bubbles formed by cavitation. Henry[13] reviewed over 1400

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man-flights under different conditions and concluded that symptom location is chiefly determined by amount of motor activity in a particular limb. However, no reports were found which included both quantification of exercise level and relationship of that level to DCS incidence with a metric allowing prediction of DCS risk in combination with other exposure parameters.

During a chamber study of chronic progressive hypoxia,[24] there was a higher incidence of DCS when exercise was performed. The value of physical relaxation to reduce DCS risk was demonstrated by Ferris.[6] This finding was considered relevant to the higher symptom incidence reported by inside observers than reported by their altitude chamber trainees who do not stand up and walk during the training exposures.

In 1987, Krutz and Dixon[21] recommended that "future work should vary both the type of exercise and energy expenditure." Although quantification of the average oxygen consumption was accomplished at ground level[17,28] and even during aircraft flight,[20,23] a reliable metric showing high correlation between level of activity and DCS risk was not reported. A recent quantification of activity level[33] during exposure to 29,500–30,000 ft (8991–9144 m; 231-226 mmHg, 4.5-4.4 psi) yielded a linear regression line with a correlation of 0.89 between the highest 1 min of oxygen consumption ($\dot{V}O_2$) during a recurring physical activity and incidence of DCS. This study was designed to test the hypothesis that a straight-line relationship between the aforementioned oxygen consumption and DCS risk is also valid at the lower, operationally significant altitude of 22,500 ft (6858 m; 314 mmHg, 6.1).

METHODS

The study was approved in advance by the Air Force Research Laboratory (AFRL) Institutional Review Board. All altitude chamber profiles, current and reported earlier, were conducted at Brooks Air Force Base/City-Base, TX (Brooks). Results and purposes of the studies are described in Cheng et al.,[3] Webb,[30] and Webb et al.[32]

This study used information from two previous altitude decompression or ground-level profiles. The altitude decompression profiles are documented in the AFRL High Altitude Decompression Sickness Database (AFRL Database)[1] or in documentation of that database.[30] Herein, the types of activity are abbreviated as Non-Amb Echo for seated rest the entire time with echo-imaging at 16-min intervals; Amb Rest for ambulatory rest with echo-imaging, which involved standing up, walking a few feet, lying down on a gurney, accomplishing the echo-imaging movements, standing up again, walking back to the chair, and resuming a seated position; and Amb EVA for ambulatory EVA with echo-imaging.[33]

Subjects

Anthropometric measurements of the subjects in these three studies are representative of USAF pilots. The 22 male subjects in the 2010[33] report accomplished all three activity levels on the same day, hence there was no difference in anthropometric measurements.

The two earlier decompression profile conditions at 22,500 ft (6858 m; 314 mmHg; 6.1 psi)[33] were used to compare with the current results at a third and lower level of activity, Non-Amb Rest. The total duration of exposure reported in the 1998[35] paper was 6 h while accomplishing either Amb-Rest or Amb EVA. The DCS incidence results were truncated to 4 h to match the exposure duration of the current study. Truncation of DCS reporting to 4 h is justified by the results from over 3000 earlier research altitude chamber flights at Brooks where fewer than four symptoms were reported to have first occurred after the exposure ended. Hence, termination to 4 h corresponds to an analogous exposure of 4 h where no DCS occurred, but might have occurred if the flight duration was longer than 4 h. In the three exposure profiles at 22,500 ft (314 mmHg; 6.1 psi) reported here, there was only one case of DCS (at 284 min[35]), which is not reflected in the table or figure.

Equipment

Oxygen consumption measurements were obtained with a Fitmate Pro Fitness & Exercise prescription device (Cosmed SRL, Rome, Italy; COSMED K4b^2 Pulmonary Function Equipment).[33] The Fitmate Pro, also from Cosmed, provided breath-by-breath oxygen consumption during a resting metabolic rate procedure accomplished 1-5 d prior to the Non-Amb Echo exposures. After approximately 10 min of acclimation to the Fitmate apparatus, one set of the mild limb movements to be accomplished during the Non-Amb Echo decompression exposure was performed. These data were converted to $ml \cdot kg^{-1} \cdot min^{-1}$. The maximum 1-min average value of $ml \cdot kg^{-1} \cdot min^{-1}$ ($\dot{V}O_2$) was used as each subject's Non-Amb Echo oxygen consumption. Without exception, the mild arm and leg movements produced the highest $\dot{V}O_2$ by each of the 20 subjects. Venous gas emboli detection utilized a Siemens Acuson ×300 echo-imaging device using procedures established during the earlier studies of altitude exposure at Brooks. These observations allowed monitoring for arterial gas emboli as a safety procedure.

Procedures

All current exposures involved ascents to 22,500 ft (6858 m; 314 mmHg, 6.1 psi) at 5000 $ft \cdot min^{-1}$ (1524 $m \cdot min^{-1}$) without breathing 100% oxygen prior to ascent. These conditions match the conditions for the exposures providing venous gas emboli (VGE) and DCS data.[34] MBU-20P masks worn by the subjects were attached to an HGU-55/P lightweight helmet for supply of 100% oxygen during ascent, exposure, descent, and postbreathe. A 2-h postbreathe of 100% oxygen was accomplished followed by a medical evaluation and relay of information regarding report of any later symptoms should those occur. The earlier cumulative reported or observed DCS was recorded during 4 h of exposure during Non-Amb Echo and accomplishing mild limb movements every 16 min during the test exposures. These movements were done to assist in release of VGE from capillaries to the heart for observation with the echo-imaging system. Echo-imaging was conducted at 16-min intervals during each exposure. Standardized termination criteria were used throughout all previous and current exposures. If DCS was observed or reported and diagnosed by the Medical Observer or Research Monitor, the exposure was terminated.

Physical activity during the Non-Amb Echo exposures was designed to emulate seated rest during cruise flight by pilots in aircraft where movement is limited, e.g., F-22 and CV-22. This level of activity is estimated to be the lowest level of oxygen consumption of pilots during flight at cruise altitude. Subjects in the earlier exposure profiles had performed either Amb Rest or Amb extravehicular activity (EVA) during their altitude exposures.[33] The Amb EVA activity consisted of three sets of mild arm exercises each hour which simulated EVA workload.[17] The exercises each lasted 4 min and consisted of the following: 1) hand-cranked cycle ergometer, 24 rpm, 4 N, alternating arms each two revolutions; 2) torque wrench, 25 ft-lb held for 5 s in each of five positions, alternating arms; and 3) rope pull, resistance of 17 kg, one pull from shoulder height to waist level each 5 s.

Statistical Analyses

Data from the current study were compared with the earlier exposures' results to test for statistical differences in DCS occurrence between exposures using Chi-squared tests accounting for low N. Linear regression lines produced via Microsoft Excel 2013 included slope and intercept equations. Student's *t*-tests were used to determine significance of differences in $\dot{V}O_2$ obtained between the results[33] and the current reported values.

RESULTS

Table I shows subject data obtained during the current and previous[35] exposures to 22,500 ft (6858 m; 314 mmHg; 6.1 psia; AFRL Database[1]) along with data from previous[33] ground-level evaluation of oxygen consumption during three different activities. These data on DCS allowed comparison with the current findings to determine the relationship between level of activity, $\dot{V}O_2$, and DCS risk.

The Non-Amb Echo exposures in the present study required an average maximum of only 4.7 ml · kg^{-1} · min^{-1} of oxygen consumption. Increasing that activity to include ambulation every 16 min (highest 1 min of oxygen consumption of 7.61 ml · kg^{-1} · min^{-1} as shown in Table I) resulted in a significant (P = 0.027; χ^2 = 4.90 with 1 degree of freedom) increase in DCS to 30%. A further increase in the activity by inclusion of Amb EVA exercises (Table I) resulted in 55% DCS, albeit not significantly higher than with Amb Rest (P = 0.11; χ^2 = 2.56 with 1 degree of freedom). There was a significant difference between the Non-Amb Echo $\dot{V}O_2$ of 5.4 ml · kg^{-1} · min^{-1} reported in Webb et al.[33] and the Non-Amb Echo $\dot{V}O_2$ of 4.7 ml · kg^{-1} · min^{-1} in the current study. Use of different subjects[33] with different anthropometrics may have contributed to this difference. Subjects in the ground-level study[33] were lighter than the subjects reported in this study and in the 1998[35] study ($P \leq 0.01$).

Fig. 1 shows a linear relationship with high correlation (r = 0.99) between DCS incidence and $\dot{V}O_2$ for the present study conducted at 22,500 ft (6858 m; 314 mmHg, 6.1 psi). An analogous figure showing DCS incidence[35] and the highest 1 min of $\dot{V}O_2$ for their respective activities at 29,500–30,000 ft (8991–9144 m; 231–226 mmHg, 4.5–4.4 psi),[33] shows a similar, linear slope. However, the higher altitude experienced during that 1998 study resulted in higher levels of DCS.

DISCUSSION

Despite the many research efforts, defining a quantifiable relationship between physical effort (activity) and DCS risk was either not determined or inadequately analyzed to allow using it to predict DCS risk. The current effort was designed to determine if a high correlation between $\dot{V}O_2$ and DCS risk holds true at 22,500 ft (6858 m; 314 mmHg, 6.1 psi) and to describe the nature of that relationship and its relevance to data from studies at higher altitude. The current research involved prospective ground-level analysis of the $\dot{V}O_2$ of 20 male subjects who performed Non-Amb Rest for 4 h of zero-prebreathe exposure to 22,500 ft (314 mmHg, 6.1 psi).

It must be noted that the 5.45 ml · kg^{-1} · min^{-1} value determined for Non-Amb Echo exposure $\dot{V}O_2$ results during the Webb et al.[33] study is significantly higher (P = 0.044) than the analogous value of 4.66 ml · kg^{-1} · min^{-1} determined during the current study. Anthropometrics of the subjects in the current

Table I. Male Subjects' Data from Webb et al. (1998,[35] 2010,[33] and Current Study).

PROFILE (STUDY REPORT)*	WT, KG†	HT, CM†	BMI†	BODY FAT†	AGE†	$\dot{V}O_2$§,† ml · kg^{-1} · min^{-1}	VGE	DCS
Amb EVA (1998; *N* = 20)	87.3 (8.4)	180 (7)	26.9 (2.5)	20.6 (4.0)‡	20.2 (5.3)		90%	55%
Amb EVA (2010; *N* = 22)	79.0 (11.3)	178 (8)	25.0 (3.3)	15.6 (6.8)	31.1 (7.9)	11.22 (2.35)		
Amb Rest (1998; *N* = 20)	87.3 (8.2)	180 (7)	26.9 (2.4)	20.6 (4.0)‡	29.5 (5.3)		80%	30%
Amb Rest (2010; *N* = 22)	79.0 (11.3)	178 (8)	25.0 (3.3)	15.6 (6.8)	31.1 (7.9)	7.61 (1.16)		
Non-Amb Echo (2010; *N* = 22)	79.0 (11.3)	178 (8)	25.0 (3.3)	15.6 (6.8)	31.1 (7.9)	5.45 (1.48)		
Non-Amb Echo (Current *N* = 20)	90.8 (13.5)	183 (7)	27.2 (3.5)	19.0 (6.5)	29.8 (5.3)	4.66 (0.88)	0%	0%

* Anthropometric, VGE, and DCS data from the AFRL High Altitude Decompression Sickness Database.[1] Anthropometric data and physiological data were recorded ≤1 wk prior to altitude chamber exposure.

† Mean (SD).

‡ Only 19 of the 20 subjects had a recorded body fat %.

§ Highest 1 min of $\dot{V}O_2$, ml · kg^{-1} · min^{-1} during each activity, with limb articulations every 16 min.

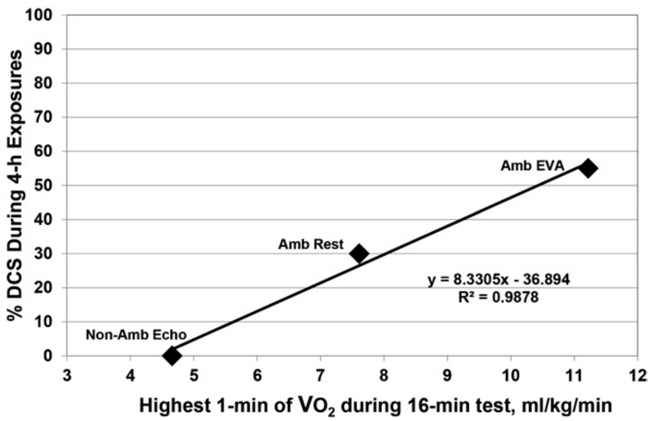

Fig. 1. DCS during zero-prebreathe, 4-h exposures of men to 22,500 ft (6858 m; 314 mmHg; 6.1 psia; r = 0.99). As reported in Webb,[33] 22 male subjects accomplished both Amb Rest and Amb EVA oxygen consumption determinations. For the current study, 20 additional subjects accomplished the Non-Amb Echo exposures.

study were more like those subjects in the 1998 study than they were to the subjects in the 2010 study, which had higher Non-Amb Echo $\dot{V}O_2$. In particular, the body weight of the current study's subjects was very close to the subject's body weight in the 1998[35] report ($P = 0.34$) and significantly higher than the subjects used for the 2010[33] study ($P \leq 0.01$). This difference may have influenced the difference between the current study and the 2010 study, leading to our decision to use the only available Non-Amb Echo data from this study in combination with the Amb EVA and Non-Amb EVA $\dot{V}O_2$ from the 2010[33] research.

The findings reported here represent the first verification of which we are aware that demonstrates a highly correlated relationship between quantified levels of activity and DCS risk. The data could be used to update current DCS risk-prediction models by correction of the activity level effects on DCS risk during exposure.[19,26] The results may also help explain the higher DCS risk for inside observers than for seated trainees. Inside observers occasionally stand up and walk to a trainee to provide assistance during the training exposure. The trainees do not stand up or walk during altitude chamber training.

A limitation of this study is the combination of retrospective and prospective data used to develop our conclusion that $\dot{V}O_2$ is highly correlated with DCS risk. Our precautions to very closely adhere to procedures regarding performance of activity during exposure help to reduce the potential problems of using retrospective data. These precautions were based on minute-by-minute records of exposure activity and other standardized procedures during our research from the mid-1980s to the current effort. Other consistencies included the same Principal Investigator, facilities, termination criteria, and safety precautions.

These data may allow expansion of physiological envelopes of some high-altitude aircraft operations or allow reduced prebreathe requirements to obtain adequate DCS protection. The results provide information which could be used to more precisely estimate DCS risk between 22,500 feet (6858 m; 314 mmHg, 6.2 psia;) and 29,500-30,000 ft (8991–9144 m; 231–226 mmHg, 4.5–4.4 psi;).[34] Extrapolation above or below that range of altitude exposure would require further research.

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