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14. ABSTRACT INTRODUCTION: Space Shuttle extravehicular activity (EVA) requires decompression from sea level pressure (14.7 psia) to a 4.3 psia (30,300 ft) pressure suit. The transition currently involves altering the shuttle atmosphere to allow shirt-sleeve denitrogenation to occur during a 12 to 36-h staged decompression (SD) at 10.2 psia (9,800 ft) with an oxygen-enriched breathing gas (26.5% oxygen, 73.5% nitrogen). The denitrogenation provides protection from decompression sickness (DCS) during EVA in a 4.3 psia pressure suit. Our goal was to determine the highest altitude at which SD while breathing 100% oxygen (SD100) could provide effective protection from development of DCS symptoms after further decompression to 29,500 ft (4.5 psia). METHODS: There were 30 male subjects exposed to at least six of 11 conditions in random order on successive months to 29,500 ft for four hours while performing mild exercise and being monitored for venous gas emboli (VGE) with an echo-imaging system. The subjects received 15 min of ground-level (GL) preoxygenation and an additional 60 or 120 min of SD100 at one of four altitudes between 8,000 ft (10.9 psia) and 18,000 ft (7.3 psia). Control exposures followed a 75- or 135-min ground-level preoxygenation. RESULTS. During SD100, one case of DCS occurred at 18,000 ft, but not at lower staging altitudes. Higher levels of VGE were observed during SD100 at 18,000 ft than during SD100 at any lower altitude. CONCLUSION: Staged decompression at 16,000 ft and below results in decompression risk during subsequent decompression to 29,500 ft similar to that following equivalent periods of ground-level preoxygenation.					
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The Effect of Staged Decompression While Breathing 100% Oxygen on Altitude Decompression Sickness

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Introduction: Space Shuttle extravehicular activity (EVA) requires decompression from sea level pressure (14.7 psia) to a 4.3 psia (30,300 ft) pressure suit. The transition currently involves altering the shuttle atmosphere to allow shirt-sleeve denitrogenation to occur during a 12 to 36-h staged decompression (SD) at 10.2 psia (9,800 ft) with an oxygen-enriched breathing gas (26.5% oxygen, 73.5% nitrogen). The denitrogenation provides protection from decompression sickness (DCS) during EVA in a 4.3 psia pressure suit. Our goal was to determine the highest altitude at which SD while breathing 100% oxygen (SD100) could provide effective protection from development of DCS symptoms after further decompression to 29,500 ft (4.5 psia). **Methods:** There were 30 male subjects exposed to at least 6 of 11 conditions in random order on successive months to 29,500 ft for 4 h while performing mild exercise and being monitored for venous gas emboli (VGE) with an echo-imaging system. The subjects received 15 min of ground-level (GL) preoxygenation and an additional 60 or 120 min of SD100 at one of four altitudes between 8,000 ft (10.9 psia) and 18,000 ft (7.3 psia). Control exposures followed a 75- or 135-min ground-level preoxygenation. **Results:** During SD100, one case of DCS occurred at 18,000 ft, but not at lower staging altitudes. Higher levels of VGE were observed during SD100 at 18,000 ft than during SD100 at any lower altitude. **Conclusion:** Staged decompression at 16,000 ft and below results in decompression risk during subsequent decompression to 29,500 ft similar to that following equivalent periods of ground-level preoxygenation.

Keywords: altitude, DCS, VGE, emboli, decompression sickness, denitrogenation, preoxygenation, prebreathe.

TISSUE OXYGEN from inspired air is metabolically used to oxidize food to form CO₂ and H₂O, lowering tissue oxygen concentration to a level precluding oxygen supersaturation of tissues during reduction of barometric pressure, i.e., decompression. However, inspired nitrogen is not altered by tissue metabolism and tissues become supersaturated with nitrogen during decompression. Altitude decompression sickness (DCS) is caused by gas bubble formation resulting from tissue nitrogen supersaturation. The risk of DCS is routinely reduced by breathing 100% oxygen (preoxygenation or prebreathing) as a way of removing the tissue nitrogen prior to ascent to altitude.

Nitrogen removal, or denitrogenation, occurs during preoxygenation because of the gradient created by lack of nitrogen in the inspired gas (3). As the nitrogen-saturated venous blood enters the lungs, the nitrogen

from the blood diffuses into the alveoli, and is expired. Following the same principle, denitrogenation will occur any time venous blood contains a higher partial pressure of nitrogen than the inspired gas. This principle has been put to practical use by NASA during preparation for extravehicular activity (EVA). The space shuttle is decompressed from 14.7 psia (sea level) to 10.2 psia (Table I) and the nitrogen concentration of the shuttle atmosphere is reduced from 79% to 73.5%, thereby reducing the partial pressure of nitrogen from 11.5 to 7.5 psia (11). This staged decompression (SD) for at least 12 h, terminating with 1 h of 100% oxygen breathing, has allowed further decompression to the EVA pressure suit environment of 4.3 psia without reports of DCS.

Denitrogenation by breathing air at pressures less than 1 atmosphere, e.g., residence at altitude, was described by Gray (6) as an effective means of protection against DCS, albeit not ordinarily available. Balke (1) and Clark et al. (4) stated that residence at 14,160 ft (8.6 psia) for 2 d (2-d SD) resulted in no DCS when the subjects were then exposed to altitudes between 42,000 to 56,000 ft (2.5-1.2 psia) for a total time of 30 to 40 min. By comparison, their experiments involving decompression from sea level showed that even 4 to 6 h of breathing 100% oxygen "did not offer complete protection against DCS." In another experiment, Balke (2) stated that after living at 13,800 ft (8.7 psia) for 5 d, decompression to 40,000 ft (5.6 psia) for 2 h while performing light work (breathing 100% oxygen) resulted in no DCS symptoms. He acknowledged that

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TABLE I. ALTITUDE-PRESSURE CONVERSIONS RELATED TO THIS STUDY.

Altitude, ft	Altitude, m	Pressure, mm Hg	Pressure, psia
8,000	2438	564	10.9
12,000	3658	483	9.3
16,000	4877	412	8.0
18,000	5487	379	7.3
29,500	8992	231	4.5
Space Shuttle staged decompression pressure environment			
9,800	2987	527	10.2

denitrogenation while breathing air at reduced pressure takes several days and is, therefore, operationally impractical. This is particularly true at altitudes above 10,000 ft (10.1 psia) where hypoxia symptoms would be significant.

Staged decompression while breathing 100% oxygen (SD100) has received considerable interest for over half of the 20th century because it could significantly increase flexibility during high altitude aircraft operations. Fraser (5) found that SD100 at altitudes up to 27,500 ft (4.9 psia) for up to 1 h resulted in a marked reduction in the incidence of disabling DCS during subsequent exposure to 35,000 ft. The effectiveness of SD100 during his studies at 27,500 ft was less than the analogous SD100 at 10,000 or 20,000 ft (6.8 psia). Gray (6) reviewed the previous work on denitrogenation, showing its effectiveness in several tests up to at least 20,000 ft. On the basis of a series of altitude experiments, Henry (7) recommended that "inflight denitrogenation [SD100] for the prevention of aeroembolism symptoms should therefore be carried out at 10,000 to 15,000 ft." In his experiments, "protection was achieved by reducing symptom intensity rather than delaying onset of aeroembolism." In summarizing his data, Henry stated that "silent bubbles can originate at 15,000 ft [during SD100] when there is exercise." Venous gas emboli (VGE) as detected with non-invasive echo-imaging and Doppler ultrasound equipment was not available in the 1950's to verify this hypothesis. A more recent report verified that VGE occurred at 15,000 ft (8.3 psia) (15). The importance of bubble formation at potential SD100 altitudes has been emphasized as a factor in symptom development during further decompression (12). VGE are also a means of evaluating decompression stress, particularly in the absence of DCS symptoms (15,17).

Marbarger et al. (9) carefully examined the rate of denitrogenation and subsequent incidence of DCS in 33 male subjects during 2-h exposures to 38,000 ft (3.0 psia) following 2 h of SD100 at 8,000 ft, 12,000 ft, 18,000 ft, and 22,000 ft (6.2 psia). As compared with a ground-level (GL) control preoxygenation, after which two cases of DCS were observed, they reported no significant differences between preoxygenation effectiveness in preventing DCS at any of the selected SD100 altitudes. However, since at least 24 of the 33 subjects did not develop DCS, the comparison of SD100 effectiveness relied on an N of only 9 cases of DCS, 4 of which may have been observed in the same 2 subjects.

In the more than 40 years since the report by Marbarger et al. (9), there have been significant changes in

the definition of acceptable limits of symptom development in human subjects (16). The currently accepted symptom endpoints include much milder manifestations compared with the serious and often intolerable DCS symptom endpoints of the 1940's and 50's. Using these milder symptoms as test termination criteria obviously increases the incidence of DCS in the otherwise comparable current studies.

Operationally, some of these milder symptoms of slight pain or paresthesia may be masked by equipment constraints, may be confused with causes other than DCS, and may not be reported at all because of concern for mission completion and career protection. However, in the laboratory, reporting of *all* symptoms by the subjects leads to a clearer picture of decompression stress and allows for more accurate development of countermeasures. In addition, the advent of a method to non-invasively visualize VGE using echocardiography has allowed a comparison based on this more objective criteria for comparing severity of exposure when the exposure does not result in symptom development. For these reasons, this study re-examined the efficacy of SD100. The goal of the current research effort was to determine the highest altitude at which SD100 could provide effective protection from development of DCS symptoms after further decompression to 29,500 ft.

METHODS

The voluntary, fully informed consent of the subjects used in this research was obtained in accordance with AFI 40-402. Thirty male subjects participated in a total of 248 exposures during the study. Although not all of the subjects completed each profile, each subject completed at least 6 of the 11 profiles. All subjects passed an appropriate physical examination, and were otherwise representative of the USAF rated aircrew population. They were not allowed to participate in SCUBA diving, hyperbaric exposures, or flying for at least 48 h before each scheduled altitude exposure.

Prior to each altitude exposure, the medical monitor conducted a short physical examination of subjects to identify any signs of illness or other problem that would endanger the subject or bias the experimental results. Prior to beginning preoxygenation, each subject was taken to 5,000 ft (12.2 psia) simulated altitude in the altitude chamber at a rate of 5,000 ft · min⁻¹ for an ear and sinus check. Time spent at 5,000 ft was less than 5 s. During the return to ground level at 5,000 ft · min⁻¹, the inside observer ensured that subjects were able to equalize the pressure across their eardrums.

A neck-seal respirator made by Intertechnique® (Plaisir Cedex, France) was used for oxygen delivery during preoxygenation and exposure. This mask provided a slight, 2 cm of water, positive pressure, which reduced the opportunity for inboard leaks of nitrogen from the atmosphere, and was more comfortable than the standard aviator's mask. Breathing gas during preoxygenation and while decompressed was 100% oxygen (aviator's breathing oxygen; normal analysis 99.7-99.8% oxygen).

Ascent and descent were accomplished at 5,000 ft · min⁻¹. The final altitude of 29,500 ft was chosen after

TABLE II. RESULTS AT 29,500 FT FOLLOWING CONTROL AND TEST PREOXYGENATION PROCEDURES.

Condition	Parameter	N	75 min Preoxygenation	N	135 min Preoxygenation
GL Control	VGE	15	67%	30	47%
GL Control	DCS	15	40%	30	40%
Condition	Parameter	N	60 min SD100*	N	120 min SD100*
8K SD100	VGE	15	80% ^{1,2}	15	53%
	DCS	15	60%	15	47%
12K SD100	VGE	15	80%	15	53%
	DCS	15	67% ^{1,2}	15	40%
16K SD100	VGE	29	83% ¹	30	63%
	DCS	29	48%	30	43%
18K SD100	VGE	28	79% ^{1,2}	26	77% ^{1,2}
	DCS	28	64% ¹	26	50%

* Preceded by 15 min of ground level (GL) preoxygenation. SD100 at 8,000 ft (8K; 564 mm Hg; 10.9 psia), 12,000 ft (12K; 483 mm Hg; 9.4 psia); 16,000 ft (16K; 8.0 psia); and 18,000 ft (18K; 378 mm Hg; 7.34 psia).

Shaded sections indicate significance ($p < 0.05$) relative to GL preoxygenation control of the same total duration using:

¹ Gehan-Wilcoxon test;

² Mantel Hanzel test.

analysis of a repository of data in the Air Force Research Laboratory (AFRL) Hypobaric Decompression Sickness Research Database at Brooks AFB, TX. These data indicated that a 4-h exposure to 29,500 ft should produce approximately 50% DCS symptom incidence with 75–135 min of preoxygenation and allow a better opportunity for showing either a positive or negative difference in SD100 effectiveness.

Prior to the test exposures, the subjects received 15 min of ground-level (GL) preoxygenation and an additional 60 or 120 min of SD100 at 8,000 ft, 12,000 ft, 16,000 ft, and 18,000 ft (Tables I and II). Control exposures followed a 75 or 135-min GL preoxygenation.

At the final altitude of 29,500 ft the subjects performed an exercise/rest/monitoring cycle designed to simulate the minimal exercise experienced by a pilot flying an aircraft and required about 100-kcal · h⁻¹. The exercise consisted of a 5-min period of rope pulling every 15 min throughout the exposure. The spring-loaded rope-pull device (MGI Mini Gym® Model 180) was marked at a peak resistance of 75.6 N (17 lbs). When the timing light came on, the subject would pull the handgrip with both hands, from eye-height at arms' reach, to their lap, once each 5 s, at a rate sufficient to cause the indicator to superimpose on the peak resistance mark. The subject held the handgrip in his lap until the timing light went off (about 2 s). When the timing light went off, the subject returned the handgrip to eye-height at arms' reach to repeat the cycle. The rope-pulling exercise followed a 5-min period of rest seated in a chair and the rest was followed by a 5-min period of echo-imaging and joint flexion while reclined at the echo-imaging station.

At 15 min intervals, the subjects were monitored for presence of any VGE using a Hewlett Packard Sonos 500 or 1000 Doppler/Echo-Imaging System. These systems permit both audio and visual monitoring of gas emboli in all four chambers of the heart. The time of first observation of any VGE was recorded and used to generate Fig. 1–3.

Grading of joint pain symptoms followed the scale proposed in Webb and Pilmanis (16): *Grade 1* - Intermittent, mild to moderate pain; intermittent or constant

joint awareness or "fullness"; *Grade 2* - Constant, tolerable, mild to moderate pain with no impairment of function or performance; *Grade 3* - Tolerable pain resulting in less than 50% impairment of function or performance; *Grade 4* - Intolerable pain or pain resulting in at least 50% impairment of function or performance. Exposure endpoints were completion of 4 h at 29,500 ft (8,992 m, 231 mm Hg), the first report of joint pain exceeding Grade 1, or report of any other DCS sign or symptom (10), whichever occurred first. Symptom resolution during repressurization or during hyperbaric oxygen treatment aided validation of symptoms and the first verified time of DCS symptom occurrence was used to generate Fig. 1 and 2.

Data recorded on each subject-exposure included: subject anthropometrics and injury history, exposure parameters, symptom descriptions and onset times, and echo-imaging results (17). Statistical methods employed to determine if differences were evident in the proportion of DCS over time between exposure profile results included the Gehan-Wilcoxon test (8), Mantel Hanzel test (8), Chi Square test, or Fisher's Exact test as appropriate. The null hypothesis for each test was that there is no difference between the curves and/or final percentage of incidence.

RESULTS

One case of DCS occurred during SD100 at 18,000 ft, but no DCS occurred during preoxygenation at lower SD100 altitudes. In the absence of DCS symptoms, the level of VGE may be used to provide an alternative measure of exposure severity. Of the 173 SD100 exposures, 12 resulted in VGE at the stage altitude; 9 of these at 18,000 ft. Although the level of VGE at the 120-min 18,000-ft stage was three-fold greater than at any lower stage altitude, it was not statistically different ($p = 0.07$; Fisher's Exact test). Nonetheless, there was a trend toward greater severity of exposure following SD100 at 18,000 ft as indicated by level of VGE at 29,500 ft (Fig. 2).

Table II summarizes results from exposures to 29,500 ft following GL denitrogenation and SD100. Significant differences between the percentage of VGE or DCS

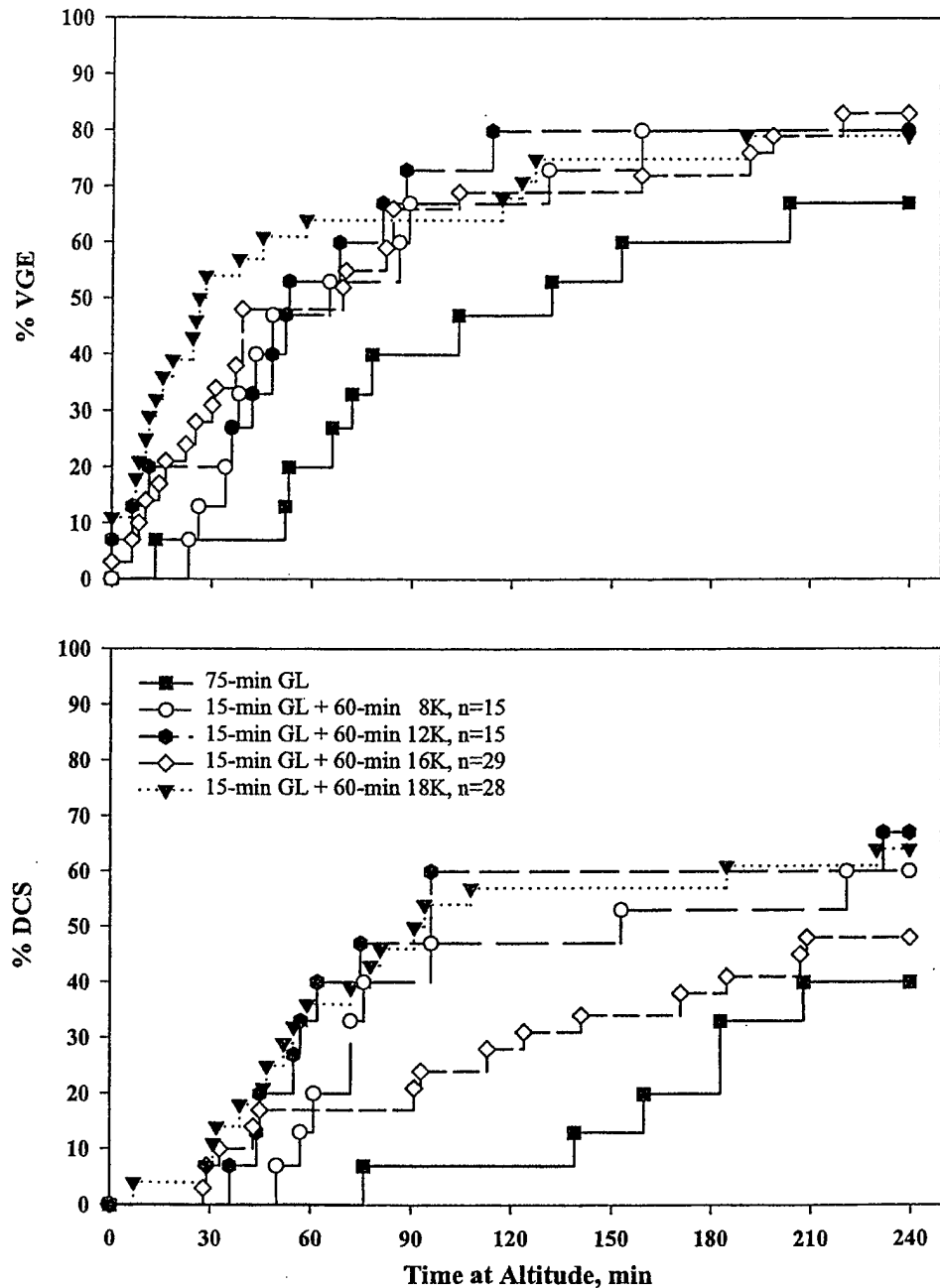


Fig. 1. VGE and DCS latency following 75-min denitrations.

incidence following SD100 vs. GL preoxygenation of equivalent time are shown as shaded cells in Table II. The methods used to determine significance tested the overall difference of the onset curves (Fig. 1 and 2) rather than the final, cumulative percentage observed after 4 h of exposure at 29,500 ft (Table II). Standard errors on the DCS and VGE onset curves maximized at $\pm 9.8\%$ when the N was 26–30 and $\pm 12.9\%$ when the N was 15.

Three of four comparisons of SD100 at 18,000 ft vs. GL denitrogenation showed a significant increase of incidence at 29,500 ft (Table II). In contrast, SD100 at 8,000 ft vs. GL denitrogenation, 12,000 ft vs. GL denitrogenation, and 16,000 ft vs. GL denitrogenation each showed significance in only one of the four compari-

sons. The level of VGE following SD100 for 120 min at 18,000 ft was also higher ($p < 0.05$; Gehan-Wilcoxon test and Mantel-Haenszel test) than the VGE levels following SD100 at 8,000 ft, 12,000 ft, and 16,000 ft.

DISCUSSION

Previous efforts in our laboratory using 1 h of GL preoxygenation for exposures to 30,000 ft showed an incidence of VGE and DCS of approximately 80% (13,14). The lower level of DCS observed here, albeit not significant, may reflect the lighter level of exercise performed during decompression as observed by Pilmanis et al. (10).

Exposure severity following SD100 at or below 16,000

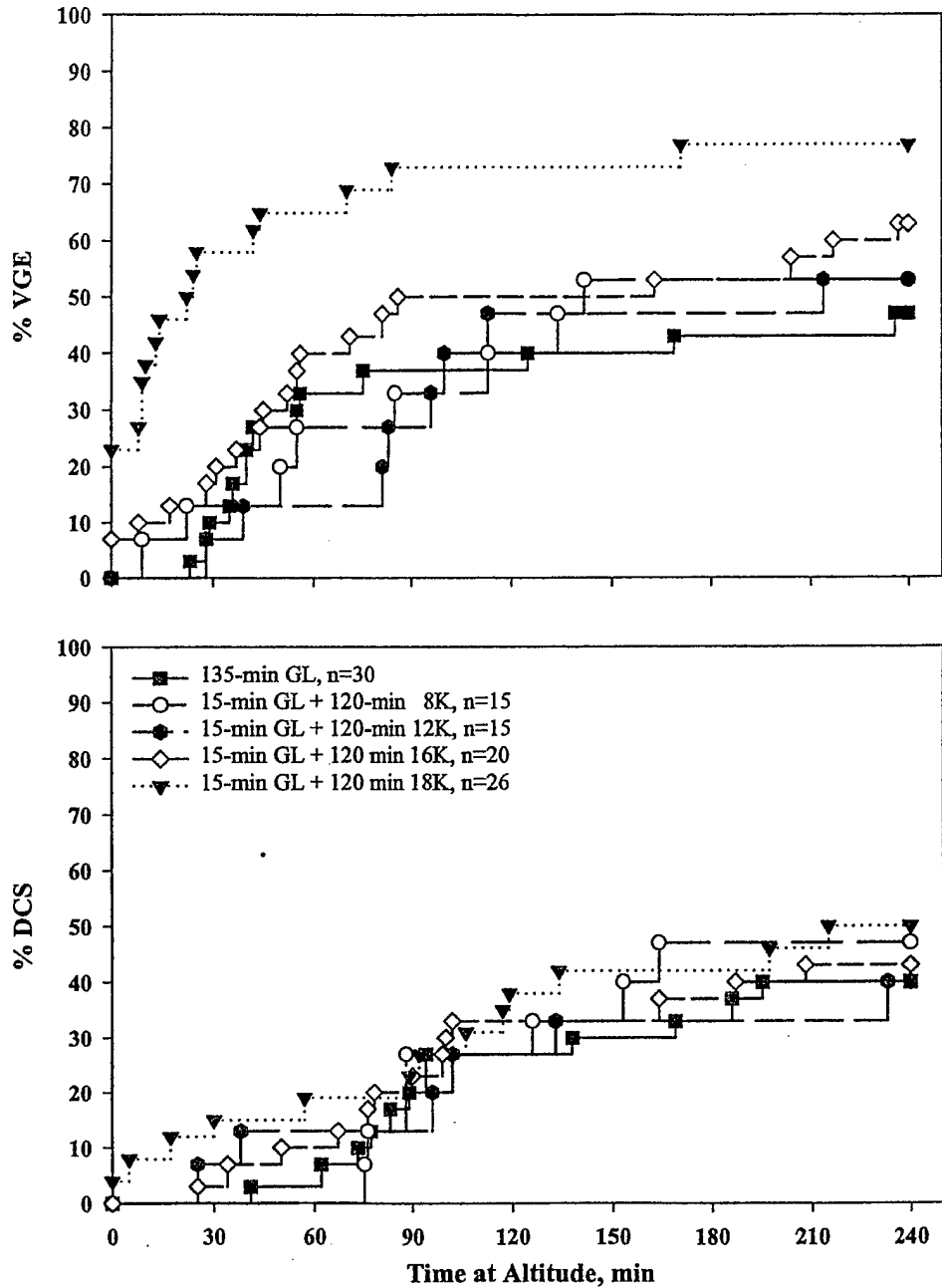


Fig. 2. VGE and DCS latency following 135-min denitrogenations.

ft appears to be low, especially when alternative measures of exposure severity, VGE levels, are compared with those following SD100 at 18,000 ft. VGE onset rate was significantly faster relative to GL preoxygenation following both durations of SD100 at 18,000 ft. The trend toward higher DCS and VGE levels during and following SD100 at 18,000 ft (Fig. 3) is reason to preclude recommendation for use of SD100 at 18,000 ft and higher. This result differs from the Marberger (9) report which did not find any significant difference, even with SD100 at 22,000 ft. The reason is partly due to inclusion of VGE as an indicator of decompression stress. The high level of VGE observed at 29,500 ft after SD100 (four of eight comparisons showed significance) is the most consistent indicator that SD100 at higher altitudes

may represent an increase in subsequent exposure severity not manifested by differences in symptom incidence. The one case of DCS during SD100 at 18,000 ft, although not significant, indicates at least some personnel using SD100 at 18,000 ft would be precluded from further ascent, possibly limiting further decompression of other personnel.

The results of this study imply the potential for operational employment of SD100 at 16,000 ft and below. The lower DCS incidence with SD100 at 16,000 ft (Table II, Fig. 1) may imply better denitrogenation due to non-symptomatic VGE elimination in the lungs or nitrogen elimination via the skin due to greater differential nitrogen pressure than at ground level.

For military aviation, these results indicate relative

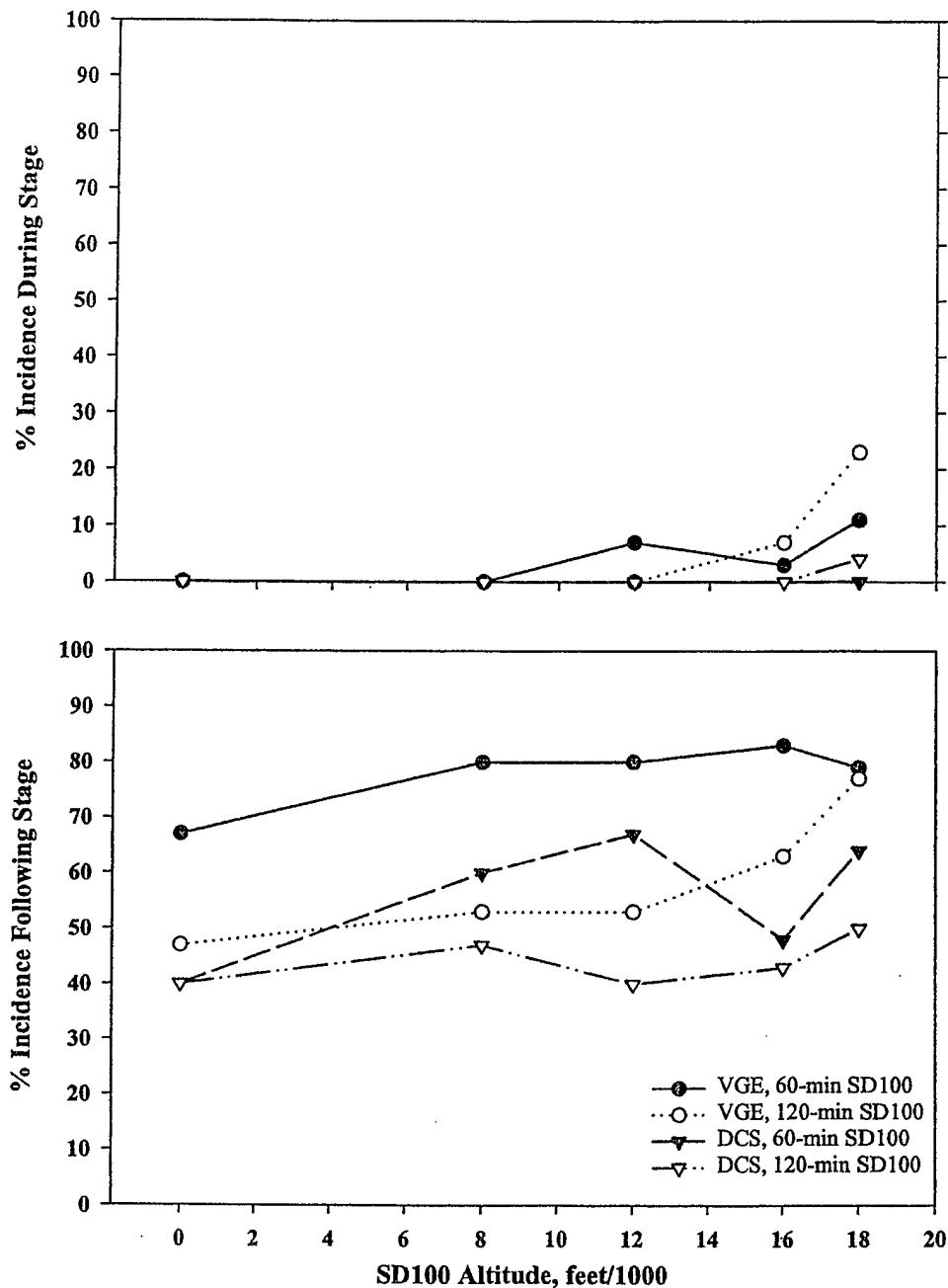


Fig. 3. VGE and DCS incidence during and following SD100.

safety from DCS during final decompression following denitrogenation during cruise at or below 16,000 ft cabin altitude. Thus, a loss of cabin pressure in a fighter aircraft at 30,000 ft after a significant period of exposure time at 15,000 ft cabin pressure while breathing 100% oxygen should result in minimal risk of DCS. In contrast, a cabin pressure of 18,000 ft or higher will carry a much greater DCS post-rapid decompression penalty. For instance, future high altitude ($\geq 50,000$ ft) fighter aircraft, e.g., the USAF F-22 and Eurofighter, will be able to cruise at or above 50,000 ft with pressurization systems that expose the pilot to $\geq 20,000$ ft in the cockpit where VGE onset occurs rapidly (17). Rapid decompression in such craft from 20,000 ft to $\geq 50,000$ ft (1.7 psia) would allow rapid growth of existing VGE (12) and the probability of more

rapid onset of symptoms. If, in normal operations, 100% oxygen was not the breathing gas, the additional nitrogen may increase risk of VGE and/or DCS (3,15). The current findings are in agreement with the report by Henry (7), and tends to verify his statement about "silent" bubble formation at 15,000 ft.

The finding that SD100 altitudes up to 16,000 ft provide effective denitrogenation also implies the potential for transition to this region of pressure as a space vehicle or extraterrestrial habitat atmospheric pressure. Such a pressure would allow easier transition to a low pressure suit, e.g., 3.0–3.5 psia, than could be achieved with the current 10.2 psia staged decompression. The current 10.2 psia staged decompression could not provide adequate protection without additional denitroge-

nation by breathing 100% oxygen. The value of a 3.0–3.5 psia pressure suit lies in its economy, simplicity, lower weight, ease of maintenance, and ease of mobility. The weight of the current 4.3 psia Space Shuttle suit may be of little consequence during EVA, but it would be unmanageable even at the low Lunar gravity due to extensive modification, added weight, since the Apollo Moon walks. If extraterrestrial habitat pressures could be reduced to the equivalent of at least 16,000 ft, extra-habitat activity in a low pressure suit would benefit from greatly reduced DCS risk and advantages of a low pressure suit. The use of a 3.0 psia pressure suit while breathing 100% oxygen should provide the individual with an alveolar P_{O_2} very similar to breathing air at 10,000 ft. With reasonably timed acclimatization during transit, the level of hypoxia at a 10,000-ft air-breathing equivalent should be quite tolerable as exemplified by many terrestrial inhabitants.

CONCLUSIONS

Prebreathing to prevent DCS appears to be as effective at altitudes up to 16,000 ft as it is at ground level, but begins losing effectiveness at 18,000 ft. The current results indicate that operational scenarios which will result in sustained high cabin altitudes with little or no opportunity for GL denitrogenation could benefit from SD100 at cabin altitudes up to 16,000 ft.

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