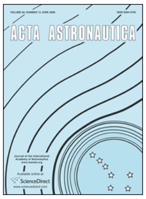
Acta Astronautica 109 (2015) 76–87

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro



Modeling a 15-min extravehicular activity prebreathe protocol using NASA's exploration atmosphere (56.5 kPa/34% O_2)

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ARTICLE INFO

Article history:
Received 27 August 2014
Received in revised form
22 October 2014
Accepted 28 November 2014
Available online 8 December 2014

Keywords:
Prebreathe
Decompression sickness
EVA
Denitrogenation
Atmosphere

ABSTRACT

NASA's plans for future human exploration missions utilize a new atmosphere of 56.5 kPa (8.2 psia), 34% O_2, 66% N_2 to enable rapid extravehicular activity (EVA) capability with minimal gas losses; however, existing EVA prebreathe protocols to mitigate risk of decompression sickness (DCS) are not applicable to the new exploration atmosphere. We provide preliminary analysis of a 15-min prebreathe protocol and examine the potential benefits of intermittent recompression (IR) and an abbreviated N_2 purge on crew time and gas consumables usage. A probabilistic model of decompression stress based on an established biophysical model of DCS risk was developed, providing significant ($p < 0.0001$) prediction and goodness-of-fit with 84 cases of DCS in 668 human altitude exposures including a variety of pressure profiles. DCS risk for a 15-min prebreathe protocol was then estimated under different exploration EVA scenarios. Estimated DCS risk for all EVA scenarios modeled using the 15-min prebreathe protocol ranged between 6.1% and 12.1%. Supersaturation in neurological tissues (5- and 10-min half-time compartments) is prevented and tissue tensions in faster half-time compartments (≤ 40 min), where the majority of whole-body N_2 is located, are reduced to about the levels (30.0 vs. 27.6 kPa) achieved during a standard Shuttle prebreathe protocol. IR reduced estimated DCS risk from 9.7% to 7.9% (1.8% reduction) and from 8.4% to 6.1% (2.3% reduction) for the scenarios modeled; the penalty of N_2 reuptake during IR may be outweighed by the benefit of decreased bubble size. Savings of 75% of purge gas and time (0.22 kg gas and 6 min of crew time per person per EVA) are achievable by abbreviating the EVA suit purge to 20% N_2 vs. 5% N_2 at the expense of an increase in estimated DCS risk from 9.7% to 12.1% (2.4% increase). A 15-min prebreathe protocol appears feasible using the new exploration atmosphere. IR between EVAs may enable reductions in suit purge and prebreathe requirements, decompression stress, and/or suit operating pressures. Ground trial validation is required before operational implementation.

1. Introduction

NASA's future human exploration missions could involve more than a thousand extravehicular activities (EVAs) per year [1]; however, current engineering and physiological constraints such as oxygen purge and prebreathe requirements make EVAs costly in terms of crew time and consumables. In recognition of this, NASA has recently adopted an exploration atmosphere of 56.5 kPa (8.2 psia), 34% oxygen (O_2), 66% nitrogen (N_2) for future spacecraft that will be used for high-frequency EVAs [2]. This new exploration

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http://dx.doi.org/10.1016/j.actaastro.2014.11.039
0094-5765/

Nomenclature

BGI	bubble growth index
DCS	decompression sickness
DT	Doppler technician
EVA	extravehicular activity
H–L	Hosmer–Lemeshow
ISS	International Space Station
JSC	Johnson Space Center
kPa	kilopascals
LL	log likelihood
MMSEV	Multi-Mission Space Exploration Vehicle
N_2	nitrogen
O_2	oxygen
$P(DCS)$	probability of decompression sickness
PLSS	portable life support system
ppN_2	partial pressure of nitrogen
ppO_2	partial pressure of oxygen
psi	pounds per square inch
psia	pounds per square inch absolute
psid	pounds per square inch differential
TBDM	Tissue Bubble Dynamics Model
VGE	venous gas emboli

atmosphere represents a change to the previously defined exploration atmosphere of 8.0 psia, 32% O_2, 68% N_2, recommended in 2006 by the Exploration Atmospheres Working Group [3]. An increase of ppO_2 from 2.56 to 2.79 psia further reduced the risk of transient Acute Mountain Sickness, and other physiological changes associated with mild hypoxia. Compared with the current International Space Station (ISS), this living environment reduces ambient ppN_2 from 11.6 psia (including argon as N_2) to 5.4 psia (no argon) and reduces ambient ppO_2 from 3.0 psia to 2.8 psia (about 1219 m equivalent air altitude) without exceeding material flammability constraints (Table 1).

When combined with suit ports that enable rapid ingress and egress with minimal gas losses, the reduced ppN_2 of the new exploration atmosphere potentially enables multiple EVAs in a single day or a single 8-h EVA, depending on mission needs. However, existing O_2 prebreathe protocols developed to protect against the risk of decompression sickness (DCS) during EVAs on ISS and the Space Shuttle are not applicable to the new exploration atmosphere—new O_2 prebreathe protocols must be developed that provide adequate protection against DCS while preserving operational flexibility and minimizing the crew time and consumables required to perform EVAs.

In this paper, we propose a 15-min prebreathe protocol and estimate the associated risk of DCS using biophysical and statistical modeling techniques. We also estimate and compare DCS risk associated with purging the EVA suit to only 80% O_2 rather than 95% O_2 as is current practice, and finally we estimate DCS risk for multiple short EVAs compared with longer continuous EVAs.

In this section, we briefly summarize information on EVA O_2 prebreathe protocols including the implications of reducing the time and gas used to purge N_2 from the EVA suit. We review the potential benefits of intermittent recompression as documented in previous human, animal, and modeling studies and then describe the combination of the new exploration atmosphere and suit ports to enable multiple EVAs per day within the context of the Multi-Mission Space Exploration Vehicle (MMSEV) and NASA's plans for human space exploration. Finally, we provide important information on the previous validation and applications of the tissue bubble dynamics model (TBDM) in the estimation of decompression stress and development of decompression protocols.

1.1. Extravehicular activity oxygen prebreathe

EVA spacesuits typically operate at low pressures (4.3–5.8 psia) to reduce the stiffness of joints in the suit and the associated effort required by astronauts to move those joints during spacewalks. Suits operate at close to 100% O_2 content to ensure that the atmosphere does not become hypoxic at these low operating pressures. However, flammability concerns preclude the use of 100% O_2 in spacecraft cabins, meaning that they must operate at higher pressures, typically 70.3–101.4 kPa (10.2–14.7 psia), to maintain an adequate partial pressure of O_2. As a result, it is necessary for crewmembers to perform O_2 prebreathe protocols before EVAs to reduce the N_2 content of their bodies ("tissue tensions") before decompression to EVA suit pressures. Failure to adequately reduce N_2 tissue tensions increases the likelihood of gas phase separation occurring during decompression, leading to the formation and growth of gas bubbles in body tissues, which is well established as a precursor to the onset of DCS symptoms [4].

Prebreathe protocols specific to spacecraft cabin atmospheres and EVA suit pressures are developed using

Table 1
Comparison of atmospheric pressure and composition for ISS, ISS staged protocols, and the exploration atmosphere. The previous (2006) version of the exploration atmosphere is also shown for reference.

	Pressure kPa (psia)	O_2 %	N_2 %	ppO_2 kPa (psi)	ppN_2 kPa (psi)
ISS	101.4 (14.7)	20.8	79.2	21.1 (3.06)	80.3 (11.64)
ISS staged prebreathe	70.3 (10.2)	26.5	73.5	18.6 (2.70)	51.7 (7.50)
Exploration atmosphere	56.5 (8.2)	34.0	66.0	19.2 (2.79)	37.3 (5.41)
Prev. exploration atmosphere (2006)	55.2 (8.0)	32.0	68.0	17.7 (2.56)	37.5 (5.44)

Table 2
Difference in off-gassing gradient resulting from purging EVA suit to 80% vs. 95% O_2. EVA suit prebreathe atmosphere for ISS and ISS staged protocols is 6.2 kPa (0.9 psi) above the ambient cabin atmosphere to ensure that the suit is adequately inflated during purge and prebreathe. Because the exterior of the EVA suit on a suit port is at vacuum, it is unnecessary to pressurize the suit above the interior cabin pressure.

	Initial saturation atmosphere	EVA suit prebreathe atmosphere	Off-gassing gradient	Difference in gradient (80% O_2 vs. 95% O_2)
ISS	101.4 kPa (14.7 psia)@20.8% O_2, 79.2% N_2	107.6 kPa (15.6 psia)@95.0% O_2, 5.0% N_2	74.4 kPa (10.8 psi)	15.8 kPa (2.3 psi)
		107.6 kPa (15.6 psia)@80.0% O_2, 20.0% N_2	58.6 kPa (8.5 psi)	
ISS staged	70.3 kPa (10.2 psia)@26.5% O_2, 73.5% N_2	76.5 kPa (11.1 psia)@95.0% O_2, 5.0% N_2	47.6 kPa (6.9 psi)	11.1 kPa (1.6 psi)
		76.5 kPa (11.1 psia)@80.0% O_2, 20.0% N_2	36.5 kPa (5.3 psi)	
Exp. atm. (MMSEV)	56.5 kPa (8.2 psia)@34.0% O_2, 66.0% N_2	41.4 kPa (6.0 psia)@95.0% O_2, 5.0% N_2	35.2 kPa (5.1 psi)	6.2 kPa (0.9 psi)
		41.4 kPa (6.0 psia)@80.0% O_2, 20.0% N_2	29.0 kPa (4.2 psi)	

models of decompression stress and are validated using ground trials to ensure that the protocols reduce the risk of DCS to within predefined acceptable levels, which may vary among missions or programs [5]. Several O_2 prebreathe protocols have been developed for use on the ISS, but each begins at 101.4 kPa (14.7 psia), 20.8% O_2, and requires several hours of preparation, 100% O_2 prebreathing, and airlock depressurization before an EVA commences [6], making multiple short EVAs inefficient in terms of crew time and gas losses. No prebreathe protocols have been developed for the new exploration atmosphere.

1.2. Abbreviated suit purge

The low operating pressures of EVA spacesuits make it necessary to ensure that the O_2 concentration inside the suits is high enough to maintain an adequate partial pressure of O_2 to sustain the crewmember. This is achieved after crewmembers don their EVA suit by flowing large volumes of O_2 into the suit, purging the N_2. A typical suit purge on the ISS will achieve $\geq 95\%$ O_2 after 8 min and requires about 0.29 kg (0.65 lb) of O_2. In an airlock, most of this gas is reclaimed at the cost of the time and power needed to operate gas reclamation pumps as well as the mass of the pumps themselves. With a suit port on an MMSEV, this gas would be vented to vacuum because the small volume (12 m^3) and high O_2 content of the cabin (34%) mean that introduction of additional O_2 during suit purge would exceed the flammability limits of the cabin. The purge is therefore potentially costly in terms of gas consumption.

An abbreviated purge lasting about 2 min would save approximately 0.22 kg (0.48 lb) of gas and 6 min of crew time per person per EVA but would decrease the tissue N_2 off-gassing gradient for the subsequent prebreathe because suit O_2 might reach only 80% compared with 95% O_2 achieved during an 8-min purge. Off-gassing gradient is the difference between tissue ppN_2 and the ppN_2 being breathed by the crewmember inside the EVA suit. The difference in off-gassing gradient is only 6.2 kPa (0.9 psi) when crewmembers are saturated at the exploration atmosphere compared with 15.9 kPa (2.3 psi) if crewmembers are saturated under standard ISS conditions. The larger off-gassing gradient associated with 95% O_2 will produce faster N_2 elimination from body tissues; however, the benefit of 95% O_2 vs. 80% O_2 for denitrogenation is reduced when initial saturation pressure is 56.5 kPa (8.2 psia), 34% O_2 (MMSEV) vs. 101.4 kPa (14.7 psia), 20.8% O_2 (ISS), as there is a smaller change in off-gassing gradient (Table 2).

The estimate of 2 min and 80% O_2 used in this paper should be considered a first-order approximation and is based on interpolation of O_2 purge data from the current extravehicular mobility unit space suit. The actual O_2 percentage reached after 2 min of purge will depend on the specific design and geometry of the exploration EVA suit and its ventilation system as well as the fit of the crewmember inside the suit. As with all aspects of exploration prebreathe protocols, ground testing and possibly in-suit instrumentation will be required to ensure that an adequate O_2 percentage has been achieved.

1.3. Intermittent recompression (IR)

A consequence of the operations concept of performing multiple EVAs per day is that crewmembers will be exposed to IR, as shown in Fig. 1, which may reduce decompression stress compared with performing a single EVA of the same total duration. A variable pressure EVA suit designed to operate at up to 56.5 kPa (8.2 psid) to enable suit port operations also provides the possibility of performing in-suit recompressions mid-EVA to reduce decompression stress.

It is well established that gas bubbles form and grow before the onset of DCS symptoms [4], and the use of short periods of recompression to control gas bubble size has previously been proposed as a more effective saturation decompression strategy [7–9]. This advantage of intermittent recompression (IR) arises because the benefit of decreasing bubble size outweighs the penalty of inert gas uptake; gas bubbles decrease in size almost instantly whereas the tissue inert gas tensions increase relatively slowly.

These predictions are based on the assumption that the volume of gas in the bubble is small compared to the volume of gas in surrounding tissue. If tissues were profusely nucleated, resulting in many small bubbles, then

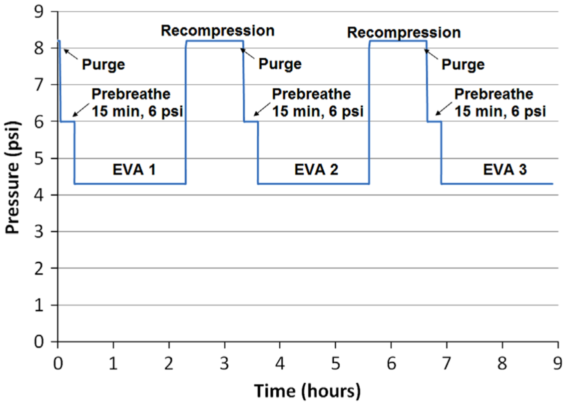

Fig. 1. Example of an EVA decompression profile during exploration with an MMSEV incorporating suit ports. This example shows three separate 2-h EVAs with 1 h of recompression between EVAs; other combinations of EVA and recompression durations are possible.

tissue tensions would decrease as the bubbles grew, with the effect of decreasing off-gassing gradients. In this case, the larger quantity of gas in the numerous small bubbles would simply redistribute into the tissue during the recompression, resulting in an equivalent decompression penalty and no decompression benefit. However, experimental data from human [10] and animal [11] decompression trials indicated significantly lower decompression stress among subjects exposed to intermittent recompressions compared with equivalent continuous exposures [8]. These findings were correctly predicted by the Tissue Bubble Dynamics Model (TBDM) [8], which is described in Section 1.5.

We have also previously used the TBDM to estimate the effects of IR on decompression stress during lunar EVAs using the pre-2013 exploration atmosphere and 95% O_2 during prebreathe and EVA [9]. On the basis of model predictions we concluded that EVAs including IR would likely reduce decompression stress in most cases, with the benefit being greater between longer EVAs where bubbles have grown larger, enabling greater reduction in bubble size during the recompression periods. Calculation of a simple tissue ratio (TR) [6] based on the initial calculated ppN_2 in a 360-min half-time compartment (ranging from 1.220 to 1.258 for the scenarios described in this paper) does not provide for the possibility of more complex biophysical effects such as the dynamics of bubbles during intermittent recompression.

In this paper we estimate the reduction in DCS risk that might result from performing multiple short EVAs using the new exploration atmosphere with IR compared with a single, longer EVA. The comparison is performed for using the new exploration atmosphere and using 80% and 95% O_2 during prebreathe and EVAs.

1.4. Exploration atmosphere and suit ports within NASA's exploration architecture

Although the principles of using IR and abbreviated purge to reduce the crew time and consumables required for EVA are applicable at current spacecraft operating pressures, the prebreathe protocols described in this paper are specific to crewmembers saturated at the exploration atmosphere of 56.5 kPa (8.2 psia), 34% O_2, 66% N_2. The only spacecraft currently planned to incorporate the exploration atmosphere and EVA suit ports is the MMSEV.

The MMSEV concept was originally developed as a pair of two-person pressurized rovers for lunar surface exploration, but after the Constellation lunar program was canceled, many of the capabilities of the MMSEV as an EVA and robotics work system for lunar surface exploration were identified as being equally important for human exploration of other destinations such as near-Earth asteroids, Mars, and Mars' moons [12–14]. One such key capability is provided by suit ports, which enable rapid EVA egress and ingress with minimal time required for crew EVA preparation and cleanup (collectively referred to as “EVA overhead”) and gas losses [15–17]. The procedures for egressing and ingressing the MMSEV via suit ports are shown, along with explanatory images, in Fig. 2. Analysis and testing have demonstrated that the combination of pressurized mobility and rapid EVA capability can increase exploration productivity by 57% while reducing the EVA time required to conduct exploration by 61%; crewmembers perform multiple short-duration EVAs in a day to conduct geological sampling at different locations while ingressing the vehicle for gross translations and geological observations [15–18].

Reducing the time that crewmembers spend in EVA suits during long-duration missions has the potential to reduce suit-induced physiological trauma and decompression stress on crewmembers, reduce consumables usage, and extend the life of EVA suits, although it should also be noted that the potentially negative implications of multiple egress–ingress cycles on suits and crewmembers are not yet understood. The capability for crewmembers to perform multiple short EVAs at different locations requires prebreathe protocols that minimize EVA overhead and gas losses while limiting the risk of DCS to within defined acceptable levels.

1.5. Tissue bubble dynamics model (TBDM): a biophysical model of decompression stress

The TBDM is a biophysical model of bubble growth in tissue [7] (Fig. 3) that has been used in development of decompression protocols for more than 25,000 commercial dives and used by NASA in the development of EVA prebreathe protocols [5]. In the model, assumed fixed values for several parameters, such as blood-tissue N_2 partition coefficient, initial radius of micronuclei, N_2 diffusivity between tissue and bubble, surface tension on a spherical bubble, and tissue bulk modulus are used to describe mass balance of tissue and bubble gases for a single growing bubble in a unit volume of tissue.

When inputted with the relevant durations, rates, pressures, and gas compositions the TBDM generates an output called bubble growth index (BGI), which is the time-varying ratio of bubble radius to an initial 3-μm radius of the bubble nucleus. The BGI for a decompression exposure is calculated over the duration of the exposure with the peak BGI value typically being used as the primary measure of decompression

Egress Procedures

1. Don Suit (56.5 kPa /8.2 psi)
2. Close/lock hatch
3. Mode to PRESS (41.4 kPa / 6.0 psi)
4. 2 min leak check in suit
5. Purge 2 min
6. Mode to EVA (41.4 kPa / 6.0 psi)
7. Start prebreathe clock
8. Vestibule depress to 24.1 kPa / 3.5 psi
9. Leak Check 1 min
10. Vestibule depress to 0.0 kPa / 0.0 psi
11. Release Suit Port

Egress Time: 11 min ± 3 min

Ingress Procedures

1. Engage Suit Port
2. Vestibule press to 56.5 kPa / 8.2 psi
3. Leak Check 1 min
4. Vestibule-Cabin press equalization
5. Vestibule-Cabin-Suit equalization
6. Open Portable Life Support System (PLSS) lock
7. Open hatch
8. Close PLSS lock
9. Egress suit

Ingress Time: 5 min ± 1 min

Depress suit to 29.6 kPa (4.3 psi) 15 min after start of prebreathe clock

Fig. 2. Suit port egress and ingress procedures (top), prototype (bottom left), and illustration of the egress/ingress method (bottom right).

$$\frac{dr}{dt} = \frac{\frac{\alpha D}{h}\left[P_a - vt + \frac{2\gamma}{r} + \frac{4}{3}\pi r^3 M - P_{Total} - P_{metabolic}\right] + \frac{rv}{3}}{P_a - vt + \frac{4\gamma}{3r} + \frac{8}{3}\pi r^3 M}$$

r = Bubble Radius (cm)
t = Time (sec)
a = Gas Solubility ((mL gas)/(mL tissue))
D = Diffusion Coefficient (cm^2/sec)
H = Bubble Film Thickness (cm)
P_a = Initial Ambient Pressure (dyne/cm^2)
v = Ascent/Descent Rate (dyne/cm^2·sec)
γ = Surface Tension (dyne/cm)
M = Tissue Modulus of Deformability (dyne/cm^2·cm^3)
P_{Total} = Total Inert Gas Tissue Tension (dyne/cm^2)
$P_{metabolic}$ = Total Metabolic Gas Tissue Tension (dyne/cm^2)

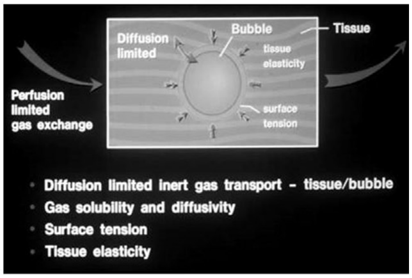

Fig. 3. Tissue Bubble Dynamics Model.

stress. Although the TBDM accommodates modeling of multiple half-time compartments to reflect the varying rates at which different body tissues take up and eliminate inert gases, the model typically includes only a 360-min theoretical half-time for tissue N_2 kinetics when it is used to estimate decompression stress during EVAs.

A statistical analysis of 6437 laboratory dives (430 DCS cases) compared predictions of the TBDM to the Workman *M*-value and the Hempleman PrT index [7]. TBDM predictions (BGI) yielded best log-likelihood and Hosmer–Lemeshow (H–L) goodness-of-fit test (Table 3). BGI also provided significant prediction ($p < 0.01$) and goodness-of-fit for DCS (H–L $p = 0.35$) and VGE (H–L $p = 0.55$) data in 345 altitude decompression exposures (57 DCS cases, 16.5% DCS, and 41.4% VGE) including prebreathe staged decompressions, all with exercise at altitude and including data points at 70.3, 41.4, and 29.7 kPa (10.2, 6.0, and 4.3 psi) [9].

In this paper we perform a logistic regression using a larger data set of 668 altitude exposures (84 DCS cases) to create a TBDM DCS Probability Model which is then used to provide quantitative estimates and comparisons of the probability of DCS ($P(DCS)$) for different prebreathe scenarios using the new exploration atmosphere.

2. Objectives

The purpose of this study was to develop and evaluate a notional EVA prebreathe protocol that minimizes crew time and gas consumables losses using the new exploration atmosphere. Specifically, the objectives of this study were as follows:

1. Use NASA human decompression data collected from 1982 to 1998 [19] to develop a probability model for DCS based on the TBDM biophysical model of bubble growth in a unit volume of tissue [7].
2. Use the TBDM DCS Probability Model to
   a. estimate the probability of DCS ($P(DCS)$) for a notional 15-min suit port prebreathe protocol,

Table 3
Comparison of TBDM with relative supersaturation and exposure index in prediction of DCS outcome in 6437 laboratory dives (430 cases of DCS). For the Hosmer–Lemeshow statistic, $p > 0.05$ rejects the hypothesis that there is a significant difference between the model predictions and the observed data.

Index	Log-likelihood	Test for improvement		Test for goodness of fit	
		χ^2	*p*-Value	χ^2	*p*-Value/df
Null set	−529	n/a	n/a	n/a	n/a
Bubble growth index	−498	62.8	<0.001	4.8	0.77/8
Relative supersaturation	−524	10.8	0.001	19.4	0.08/12
Exposure index	−505	47.9	<0.001	30.5	0.00/9

b. compare estimated $P(DCS)$ for 95% vs. 80% O_2 suit atmosphere, and
c. compare estimated $P(DCS)$ for continuous EVAs and intermittent EVAs.

3. Compare N_2 tissue tensions in 5-, 10-, 20-, and 40-min half-time compartments after a 15-min suit port prebreathe protocol with tensions in the same compartments after a standard Space Shuttle staged prebreathe protocol in which no DCS cases have been reported.

3. Methods

In this section, an empirical data set of DCS outcomes from 668 altitude exposures is used to create a logistic regression, which is a statistical model that relates the output of the TBDM (Bubble growth index) to quantitative estimates of DCS risk. The TBDM is then used to generate BGI profiles for four different EVA protocols incorporating different combinations of IR and purge durations, and the parameterized logistic regression model, described in Section 4, is used to estimate $P(DCS)$ for each protocol.

3.1. Logistic regression: relating bubble growth index to probability of DCS

Logistic regression was used to quantitatively relate BGI, the time-varying index of decompression stress from the TBDM, to an estimated probability of DCS occurring [$P(DCS)$]. Data from NASA Bends Tests 1-11b were used; these included 668 altitude exposures with 84 DCS cases (12.5% DCS, 33.8% venous gas emboli [VGE]) [20]. Data used in the logistic regression included staged decompressions from 101.4 kPa (14.7 psia) and data collected at 70.3, 44.8, 41.4, and 29.7 kPa (10.2, 6.5, 6.0, and 4.3 psia). Additional details of the data used in the logistic regression model are included in Appendix A.

The probability of DCS occurring during each test at altitude was modeled by

$$P(DCS) = \frac{\exp(B_0 + B_1 \times \mathrm{BGI})}{[1 + \exp(B_0 + B_1 \times \mathrm{BGI})]} \quad (1)$$

where B_0 and B_1 are model parameters to be estimated and the maximum BGI associated with a 360-min half-time compartment during the scheduled altitude exposure represents the decompression dose.

Estimation of model parameters was made using the logistic regression module in SYSTAT® (ver. 13) software. The program minimizes the difference between the predicted outcome from the model and the observed dichotomous DCS outcome by making small, systematic adjustments to the two parameters in the model. The optimization process continued until the absolute value of the summed log likelihood (LL) was minimized.

To evaluate the model the LL values were calculated for the constant-only model ("null model") and at the other extreme, the saturated model, wherein the predicted values of $P(DCS)$ exactly match the observed DCS incidence in each of the 37 tests. Direct assessment of the model with BGI was made by comparing predicted with actual incidence of DCS using the Hosmer–Lemeshow *C* statistic with selected bins [21].

3.2. Developing and comparing prebreathe protocols for exploration atmospheres

The TBDM was used to create time-varying BGI profiles for protocols A–D, which are described in Table 4. The parameterized logistic regression model, described in Section 4, was then used to estimate $P(DCS)$ from the peak BGI for each protocol. $P(DCS)$ was calculated after 6 h and after 8 h of EVA time for protocols A and B.

3.3. Nitrogen tensions in neurological tissues

As described above, the TBDM DCS Probability Model uses an index representing the growth of a theoretical bubble in a body tissue that assumes a 360-min half-time for N_2 gas kinetics, which is consistent with its application in the estimation of decompression stress during exposures lasting several hours. However, because of the risk of central neurological DCS resulting from supersaturation of faster neurological tissues, N_2 tensions in 5-and 10-min half-time compartments, representing the brain and spinal cord, were modeled for each protocol. The N_2 tensions in other compartments with faster half-times (≤ 40 min), where the majority of whole-body N_2 is located, were also calculated and compared with the established Shuttle staged prebreathe protocol [6], for which no cases of DCS were reported (Table 5).

4. Results and discussion

This section begins with a description of the logistic regression results, which show that the peak BGI calculated using the TBDM for each of 668 altitude exposures provides significant prediction of the resulting DCS outcomes. Goodness-of-fit statistics found no significant difference between model predictions and the observed DCS outcomes. The BGI profiles for protocols A–D are then shown and the corresponding predictions of $P(DCS)$ are calculated using the logistic regression model; all protocols are estimated to have DCS risk $\leq 12\%$ with risk being lower for shorter EVAs, EVAs including IR, and EVAs using 95% O_2. Nitrogen tissue tensions in faster half-time

Table 4
EVA protocols with different combinations of IR and O_2 breathing mixtures using the new exploration atmosphere. In all cases the balance of the gas is N_2.

Protocol A: Continuous EVA, 80% O_2					Protocol B: Continuous EVA, 95% O_2				
Step		Duration min	Pressure kPa (psi)	O_2 %	Step		Duration min	Pressure kPa (psi)	O_2 %
1	Saturated		56.5 (8.2)	34	1	Saturated		56.5 (8.2)	34
2	Purge	0:02	56.5 (8.2)	80	2	Purge	0:08	56.5 (8.2)	95
3	Depress	0:01	56.5→41.4 (8.2→6.0)	80	3	Depress	0:01	56.5→41.4 (8.2→6.0)	95
4	Prebreathe[a]	0:15	41.4 (6.0)	80	4	Prebreathe[a]	0:15	41.4 (6.0)	95
5	Depress	0:01	41.4→29.7 (6.0→4.3)	80	5	Depress	0:01	41.4→29.7 (6.0→4.3)	95
6	EVA	8:00[b]	29.7 (4.3)	80	6	EVA	8:00[b]	29.7 (4.3)	95
Protocol C: 3 × 2 h EVAs, 80% O_2					Protocol D: 3 × 2 h EVAs, 95% O_2				
Step		Duration min	Pressure kPa(psi)	O_2 %	Step		Duration min	Pressure kPa (psi)	O_2 %
1	Saturated		56.5 (8.2)	34	1	Saturated		56.5 (8.2)	34
2	Purge	0:02	56.5 (8.2)	80	2	Purge	0:08	56.5 (8.2)	95
3	Depress	0:01	56.5→41.4 (8.2→6.0)	80	3	Depress	0:01	56.5→41.4 (8.2→6.0)	95
4	Prebreathe[a]	0:15	41.4 (6.0)	80	4	Prebreathe[a]	0:15	41.4 (6.0)	95
5	Depress	0:01	41.4→29.7 (6.0→4.3)	80	5	Depress	0:01	41.4→29.7 (6.0→4.3)	95
6	EVA	2:00	29.7 (4.3)	80	6	EVA	2:00	29.7 (4.3)	95
7	Repress	0:02	29.7→56.5 (4.3→8.2)	34	7	Repress	0:02	29.7→56.5 (4.3→8.2)	34
8	Hold	1:00	56.5 (8.2)	34	8	Hold	1:00	56.5 (8.2)	34
	Repeat steps 2–8 twice, for 3 total EVAs					Repeat steps 2–8 twice, for 3 total EVAs			

[a] EVA can begin at 6 psi at the start of prebreathe, with suit pressure being dropped to 29.7 kPa (4.3 psi) 15 min after start of prebreathe clock.
[b] $P(DCS)$ was calculated after 6 h and after 8 h of continuous EVA.

Table 5
Shuttle staged prebreathe protocol.

Step		Duration (min)	Pressure kPa (psi)	O_2 %
1	Saturated		70.3 (10.2)	26.5
2	Purge	0:08	70.3 (10.2)	95
3	Prebreathe	0:40	70.3 (10.2)	95

Table 6
Parameter estimates for logistic regression.

Parameter	Coefficient	Asymptotic standard error	Z-score	p-Value	95% CI
B_0	−3.477	0.300	−11.61	< 0.001	−4.06 to −2.89
B_1	0.0499	0.0079	6.27	< 0.001	0.034–0.065

compartments are then compared and discussed, and it is concluded that neurological tissues would be adequately denitrogenated by the 15-min prebreathe thereby minimizing the likelihood of Type II DCS.

4.1. TBDM DCS Probability Model

The absolute values of the LL for the null model (constants only) and the saturated (discontinuous) model are 252.6 and 189.4, respectively. The null model is a constant-probability model based on the mean DCS incidence of 12.5% in these data, which becomes the best estimate of DCS for all 668 individuals. The LL for the null model necessarily represents a poor fit to the response variable, as BGI is assumed irrelevant to the outcome. In these same data, the LL from the discontinuous model is defined as the best that can be achieved based on the condition that the DCS incidence in each group is the true DCS incidence. The LL for the BGI (continuous) model is 231.8, and is a statistical improvement over the null model, using the likelihood ratio test with one degree of freedom ($\chi^2=41.6$, $p<0.0001$). For the BGI model, the Hosmer–Lemeshow goodness-of-fit statistic, C, was 2.70 ($p=0.26$ with 2 degrees of freedom). For the Hosmer–Lemeshow statistic, $p>0.05$ rejects the hypothesis that there is a significant difference between the model predictions and the observed data; thus, $p=0.26$ for DCS indicates that BGI provides a good fit of the data.

Parameter estimation results from SYSTAT® after Eq. (1) was submitted and are shown in Table 6. Both coefficients are statistically significant to the regression. Comparisons of observed group DCS incidence, model-predicted DCS incidence, and BGI are included below (Figs. 4 and 5). Additional details on human data are provided in Appendix A.

We conclude that BGI reasonably predicts the incidence of DCS over the range occurring in the data, which includes the range of BGI considered in this analysis of exploration prebreathe protocols, that is, BGI ranging from 15 to 30. However, predictions based on extrapolations below about 10 BGI units are conservative, with $P(DCS)$ greater than zero when BGI approaches 1 unit, at which no decompression

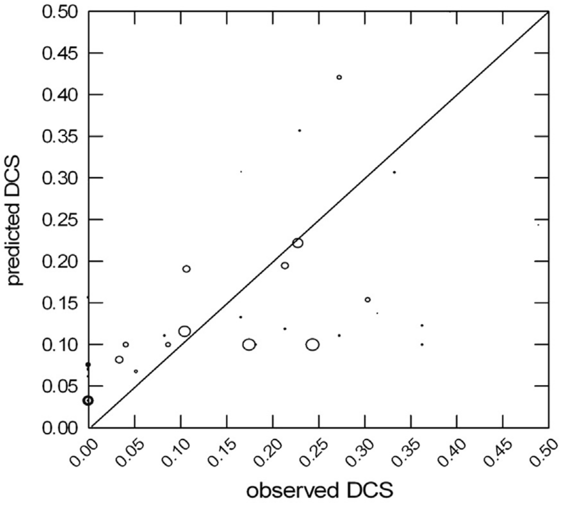

Fig. 4. Observed DCS incidence vs. model-predicted DCS incidence. Circle size reflects sample size, which in turn weights the regression. 33 of 37 tests are shown; 4 tests with sample size < 10 were omitted. Details of omitted tests are included as an appendix.

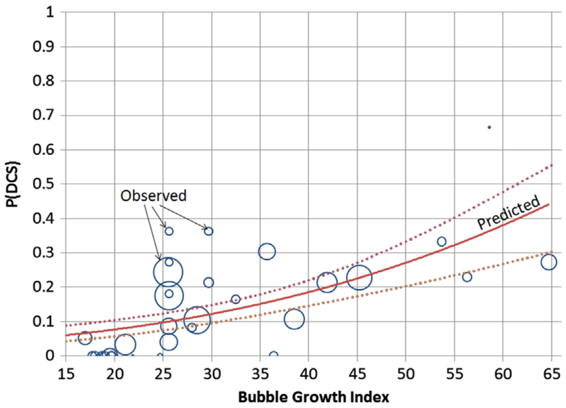

Fig. 5. Observed and predicted group DCS incidence from 37 tests shows a moderate correlation with BGI. Circle diameter reflects sample size. 33 of 37 tests are shown; 4 tests with sample size < 10 were omitted. Details of omitted tests are included as an appendix. The $P(DCS)$ and upper and lower 95% CIs are the best-fit predictions over a range of tested BGIs. Predictions are not shown for BGI < 15 units due to the absence of data in that range.

stress should be present. Additional experimental data at low stress levels may improve the prediction ability of the model for mild exposures.

The TBDM DCS Probability Model was used to estimate $P(DCS)$ for the 70.3 kPa (10.2 psi) Shuttle staged protocol that was ground tested by 35 test subjects with 22.8% reporting DCS [22] and used operationally 296 times with no reported DCS. Summary details of the ground trial are included in Appendix A, Table AI, Test 3b. Model predictions of $P(DCS)$ are shown in Table 7 for the protocol as tested in ground trials and 'as flown' during spaceflight.

The discrepancy in observed DCS between ground and flight exposures is due in part to additional prebreathe that occurred during operational implementation of the protocol during spaceflight. Detailed examination of 'as flown' protocols reveals that an additional 25 min of prebreathe is routinely included in on-orbit prebreathe protocols as a result of performing suit purge, leak check, and a slow ascent to final EVA pressure [23]. The model estimates of $P(DCS)$ for the 'as flown' protocol are based on the average of the actual prebreathe performed during the first 53 uses of the protocol on-orbit. The absence of lower-body activity and weight-bearing in microgravity before and during EVA is also likely to have reduced the risk of Type I DCS in the lower body [24] and, when combined with the additional on-orbit prebreathe, may have reduced on-orbit decompression stress to the low levels at which our models provide very conservative estimates of $P(DCS)$.

Table 7
Observed vs. model-predicted DCS incidence for Shuttle staged prebreathe protocol. 'As Flown' timelines are based on detailed timelines available from 53 EVAs. The Shuttle staged prebreathe protocol was completed 296 times on-orbit with no reported DCS.

Protocol	Sample	Predicted DCS	Observed DCS
Ground trial	35	0.23 (0.18–0.28)	0.228
As Flown	296	0.15 (0.12–0.18)	0.000

4.2. *Estimating P(DCS) for protocols A–D*

Bubble growth index profiles for each protocol are shown in Fig. 6. The peak BGI for each protocol was used in the TBDM DCS Probability Model to provide an estimate of $P(DCS)$ (Table 8). $P(DCS)$ was also estimated for protocols A and B after 6 h of EVA to allow comparison with protocols C and D while controlling for total EVA duration.

4.2.1. *Estimated P(DCS) for a notional 15-min suit port prebreathe protocol*

Model estimates of DCS risk for protocols A–D ranged from 6.1% to 12.1% (Table 8). The acceptable risk of DCS for exploration missions has not yet been defined but will take into account many factors including the acceptable probability of reduced EVA crewmember availability, frequency and durations of EVAs, modes of DCS treatment available, long-term health effects, and the likelihood of serious (Type II) DCS. During ground trials to validate prebreathe protocols for the ISS, the definition of acceptable risk of DCS was defined by the Prebreathe Reduction Program (PRP) [5] as follows:

- Accept: DCS ≤ 15% and Grade IV VGE ≤ 20%, @95% confidence level.
- Reject: DCS > 15% or Grade IV VGE > 20%, @70% confidence level.
- Any case of Type II DCS.

An important consideration in selecting the 15% level of acceptable risk was that no cases of Type II DCS were observed in 244 tests with 7692 exercising subjects until the incidence of Type I DCS exceeded 15% [5]. The model estimates of $P(DCS)$ for protocols A–D are all within the 15% limit.

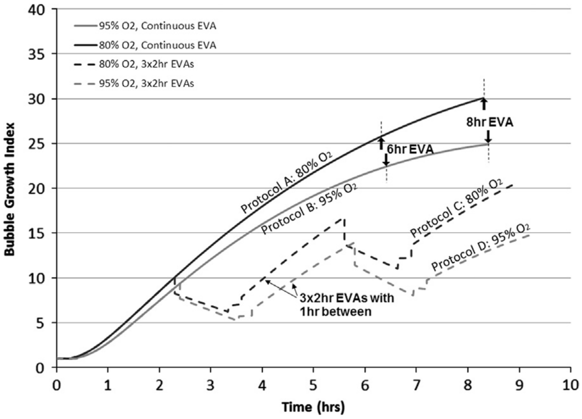

Fig. 6. Bubble growth index profiles for protocols A–D. Peak BGI from these BGI profiles were used to estimate *P*(*DCS*) using the TBDM DCS Probability Model (Table 1). The BGI after 6 h and 8 h of EVA are indicated for protocols A and B; note that the temporal offset is due to the longer duration purge for protocol B than for protocol A.

Table 8
P(*DCS*) as estimated by the TBDM DCS Probability Model. Superscript letters indicate protocols A–D.

	80% O_2	95% O_2	*Difference*
Continuous 8-h EVA	0.121^{A}	0.097^{B}	0.024
Continuous 6-h EVA	0.097^{A}	0.084^{B}	0.013
3 × 2-h EVAs	0.079^{C}	0.061^{D}	0.018
Difference: 8 h vs. 6 h	0.023	0.012	
Difference: 8 h vs. 3 × 2 h	0.041	0.035	
Difference: 6 h vs. 3 × 2 h	0.018	0.023	
Difference: 8 h 95% O_2 vs. 3 × 2 h 80% O_2:	0.017		
Difference: 6 h 95% O_2 vs. 3 × 2 h 80% O_2:	0.005		

4.2.2. Comparison of estimated P(DCS) for 95% vs. 80% O_2 suit atmosphere

As expected, estimated *P*(*DCS*) for protocols using 80% O_2 (A and C) was greater than for the corresponding protocols at 95% O_2 (B and D); however, differences in estimated risk were small. Estimated risk for an 8 h EVA with 95% O_2 is 9.7% compared with 12.1% estimated risk for the same EVA using 80% O_2, an overall increase in 2.4%. It should be emphasized that the 15-min prebreathe protocol described in this paper does not *require* an abbreviated purge; if the definition of acceptable risk requires lower *P*(*DCS*) during some or all EVAs, an extended purge and/or longer prebreathe could be performed. It is also expected that the EVA suit will leak during the course of EVAs. This normal leakage at joints and bearings in the suit will result in increasing O_2 concentration as the suit's life support system replaces leaking gas with pure O_2. Because of this, our assumption of 80% O_2 for the entire duration of EVAs may be conservative.

The implications of an abbreviated purge for crew time and consumables usage are significant when a crewmember is performing multiple EVAs per day. For example, operations concepts for lunar exploration during the Constellation program involved four crewmembers performing up to three EVAs per day, 6 days per week, during missions lasting up to 6 months [15–17]. A 6-min (75%) reduction in purge duration and 0.22 kg (0.48 lb) savings in gas usage per suit per purge would add up to more than 31 h of crew time and 816 kg (1800 lb) of gas (including tankage) per 6-month mission. The decompression benefits of performing multiple EVAs per day may also compensate for the slight increase in *P*(*DCS*) resulting from the abbreviated purge, as described in the following section.

4.2.3. Comparison of estimated P(DCS) for continuous vs. intermittent EVAs

Performing 3 × 2-h EVAs separated by 1 h at cabin pressure compared with a continuous 8-h EVA reduced estimated DCS risk by 4.1% for the abbreviated purge protocol and by 3.5% for the standard purge protocol. Comparison of the continuous 8-h EVA protocols with the 3 × 2-h intermittent EVA protocols is reasonable despite the difference in total EVA time according to data from analog field testing [15] indicating that rapid EVA capability, combined with an enhanced mobility exploration platform, will mean that less than half of the EVA time will be required to achieve the same or greater productivity relative to performing a single continuous EVA per day. Nonetheless, when compared with a single 6-h EVA, IR reduced the estimated DCS risk by 1.8% (80% O_2) to 2.3% (95% O_2), which is almost exactly the same magnitude as the increase in DCS risk estimated as a result of the abbreviated purge.

The reason for the predicted decrease in *P*(*DCS*) for the 3 × 2-h protocols is the intermittent recompressions back to cabin pressure between EVAs. The reversed N_2 concentration gradient during recompression means that N_2 reuptake from blood into the tissues slowly begins. However, at the same time, increased hydrostatic pressure rapidly reduces the size of the bubbles in those tissues such that the pressure due to surface tension inside the bubbles increases, causing a higher bubble-to-tissue N_2 diffusion gradient. Because the volume of gas in the bubbles is small compared to the volume of gas in surrounding tissues, the N_2 elimination from the bubbles does not significantly increase N_2 tissue tension. Thus, rapid EVA capability may indirectly reduce decompression stress as a result of intermittent recompressions.

As with the abbreviated purge, IR is not a required component of an exploration prebreathe protocol, but the combination of the increased hydrostatic pressure reducing bubble growth combined with the possibility of performing the same amount of work using less EVA time makes the capability of performing multiple shorter EVAs significantly enhancing for future exploration missions.

An engineering implication of donning the EVA suit at 56.5 kPa (8.2 psi), performing the first 15 min of an EVA at 41.4 kPa (6.0 psi), and then dropping suit pressure to 29.7 kPa (4.3 psi) for the remainder of the EVA is that the suit will be capable of nominal operations at 29.7, 41.4, and 56.5 kPa (4.3, 6.0, and 8.2 psid). This capability will also mean that intermittent recompressions to 6.0 or even 56.5 kPa (8.2 psi) could be performed mid-EVA even without ingressing the vehicle if an EVA was lasting longer than planned, although increased joint stiffness at the higher suit pressures would likely make this viable only for short

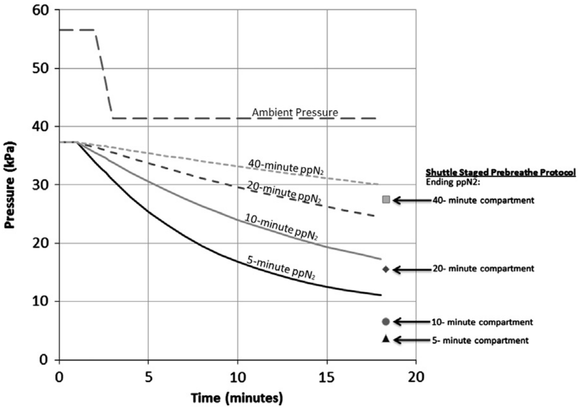

Fig. 7. Nitrogen tissue tensions calculated for 5-, 10-, 20-, and 40-min half-time compartments during 2-min purge, 1-min depress to 41.4 kPa (6.0 psi), and 15-min 80% O_2 prebreathe beginning from saturation at 56.5 kPa (8.2 psi), 34% O_2, 66% N_2. Ending ppN_2 for the Shuttle staged prebreathe protocol is also shown for comparison (40-min 95% O_2 prebreathe beginning from saturation at 10.2 psi, 26.5% O_2, 73.5% N_2).

periods or when crew workload is low. Alternatively, prebreathe protocols could be developed assuming an 8 h EVA and any IR that occurs would serve as an additional safety margin.

4.2.4. *N_2 tissue tensions in 5-, 10-, 20-, and 40-min half-time compartments*

Changes in modeled N_2 tissue tensions for 5–40-min half-time compartments are shown in Fig. 7. The ending ppN_2 for the same compartments for the modeled Shuttle staged prebreathe protocol is also shown. This is significant because 5- and 10-min compartments represent the brain and spinal cord, which are typically well denitrogenated by the end of longer duration conventional prebreathe protocols. Use of the much shorter 15-min protocol proposed here could mean that the brain and spinal cord are inadequately denitrogenated at the beginning of the EVA, presenting a risk of serious neurological DCS and, as described above, the TBDM DCS Probability Model uses a 360-min compartment to estimate $P(DCS)$ and therefore does not account for this possibility.

From Fig. 7 it can be seen that the modeled ending ppN2 for the 5-, 10-, and 20-min compartments are all below 29.7 kPa (4.3 psi), thereby avoiding the risk of supersaturation upon depressurization to the final EVA suit pressure. Although the ending ppN2 of the 40-min compartment is 30.0 kPa (4.35 psi), the difference between this and 27.6 kPa (4.00 psi) for the Shuttle staged protocol is relatively small, suggesting that the tissue tensions in the faster half-time compartments (≤ 40 min), where the majority of whole-body N_2 is located, are reduced to approximately the levels achieved during the standard 40 min, 70.3 kPa (10.2 psi) Shuttle staged prebreathe protocol [6] for which no cases of DCS were reported.

5. Conclusions

A 15-min O_2 prebreathe protocol is proposed to enable rapid EVA capability using the new exploration atmosphere of 56.5 kPa (8.2 psi)/34% O_2. A TBDM DCS Probability Model based on an existing biophysical model of inert gas bubble growth provides significant prediction and goodness-of-fit with 84 cases of DCS in 668 human altitude exposures. Model predictions suggest that 15-min O_2 prebreathe protocols used in conjunction with suit ports and an 56.5 kPa (8.2 psi), 34% O_2, 66% N_2 atmosphere may enable rapid EVA capability for future exploration missions with the risk of DCS $\leq$ 12%. EVA could begin immediately at 41.4 kPa (6.0 psi), with crewmembers decreasing suit pressure to 29.7 kPa (4.3 psi) after completing the 15-min in-suit prebreathe. Model predictions suggest that intermittent recompression during exploration EVA may reduce decompression stress from 9.7% to 7.9% (1.8% reduction) and from 8.4% to 6.1% (2.3% reduction) for 6 h of total EVA time; the penalty of N_2 reuptake during intermittent recompressions may be outweighed by the benefit of decreased bubble size.

Savings in gas consumables and crew time may be accumulated by abbreviating the EVA suit N_2 purge to 2 min (20% N_2) compared with 8 min (5% N_2) at the expense of an increase in estimated decompression risk of up to 2.4% for an 8-h EVA. Increased DCS risk could be offset by intermittent recompressions or by spending additional time at 41.4 kPa (6 psi) at the beginning of the EVA. Savings of 0.22 kg (0.48 lb) of gas and 6 min per person per EVA corresponds to 75% reduction in mass and crew time during suit purge and would save more than 31 h of crew time and 816 kg (1800 lb) of gas and tankage during a 6 month planetary surface mission.

Further research is needed to characterize and optimize breathing mixtures and intermittent recompression across the range of environments and operational conditions in which astronauts will live and work during future exploration missions. Development of exploration prebreathe protocols will begin with definition of acceptable risk, followed by development of protocols based on models such as ours, and, ultimately, validation of protocols through ground trials before operational implementation.

Acknowledgments

The authors wish to thank Dr. Jane Krauhs and James Wessel for their thorough reviews of this report. This report was made possible, in part, through a National Aeronautics and Space Administration Cooperative Agreement (NNJ11HE31A) with the Universities Space Research Association. Conclusions are those of the authors and are not necessarily endorsed by the National Aeronautics and Space Administration.

Appendix A. Additional information about the TBDM logistic regression model

Subjects

Experiments were conducted at NASA Johnson Space Center (JSC) from 1982 to 1998, all to support the program of extravehicular activity (EVA) from the Space Shuttle. All protocols were approved in advance by the JSC Committee for the Protection of Human Subjects. Subjects volunteered, provided written informed consent before participating, and were free to withdraw at any time during a trial. A physician conducted a short physical examination of subjects before each altitude exposure to identify any signs of illness or other problems that would endanger the subject or bias the results. On the morning of each exposure, subjects received a briefing that emphasized their responsibility to report any symptoms. A medical officer, independent of the research staff, ensured subject health and safety, and made the diagnosis of DCS. The mean and standard deviation of subject age and weight for 668 exposures was 31.8 years ± 7.1 and 73.5 kg ± 11.1, respectively. There were 558 exposures with men and 110 exposures with women. The mean exposure time at the final test altitude was 243 min ± 80 and the mean onset of DCS symptoms in 82 cases of DCS was 121 min ± 70; 2 subjects did not have onset time for symptoms during the altitude exposure.

Data

The data consisted of DCS outcomes from 668 human altitude chamber exposures grouped into 37 distinct denitrogenation protocols, called prebreathe protocols. Table A1 is a summary of the 37 tests. Most often the final exposure pressure was 29.7 kPa (4.3 psia), which is the nominal operating pressure of the current EVA space suit. But periods of 12–24 h were spent at 70.3 kPa (10.2 psia), the intermediate pressure stage before exposure to 29.7 kPa (4.3 psia). These exposures constitute decompression to a pressure not expected to cause DCS. No venous gas embolus (VGE) data were collected during these long periods at 70.3 kPa (10.2 psia), but any symptoms volunteered during this period were recorded. Other exposure pressures such as 41.4, 44.8, and 69.6 kPa (6.0, 6.5, and 10.1 psia) completed our testing. All subjects did a variety of repetitive exercises (including ambulation) with varying degrees of physical activity while at the final test altitude, usually in groups of 3 subjects and one Doppler technician (DT). Those who were exposed to the intermediate 70.3 kPa (10.2 psia) condition had no assigned

Table A1
Summary of tests from 1982 to 1998.

Test	P2 kPa/psia	Duration (h)	Sample		Mean age	DCS cases	DCS (%)	Mean BGI	VGE (any Grade)	VGE (Grade IV)
			m	*f*						
1a	29.7/4.3	3	11	0	34.5	4	36.3	29.7	7	4
1b	29.7/4.3	3	13	0	32.3	3	23.0	56.3	11	7
1b10.2	70.3/10.2	12	13	0	32.3	0	0	19.7	n/a	n/a
1c	29.7/4.3	3	12	0	32.0	4	33.3	53.7	7	6
1c10.2	70.3/10.2	12	12	0	32.0	0	0	19.7	n/a	n/a
1d	*29.7/4.3*	*3*	*3*	*0*	*39.6*	*2*	*66.6*	*58.6*	*3*	*2*
1d10.2	*70.3/10.2*	*18*	*3*	*0*	*39.6*	*0*	*0*	*21.9*	*n/a*	*n/a*
2a	29.7/4.3	4	23	0	31.6	7	30.4	35.7	15	8
2b	29.7/4.3	4	22	0	31.5	6!	27.3	64.7	10	7
2b10.2	70.3/10.2	12	22	0	31.5	0	0	19.5	n/a	n/a
3a	29.7/4.3	6	28	0	31.0	6	21.4	41.9	13	11
3b	29.7/4.3	6	35	0	30.1	8	22.8	45.2	20	8
3b10.2	70.3/10.2	12	35	0	30.1	0	0	1.0	n/a	n/a
3c	29.7/4.3	6	14	0	32.5	3	21.4	29.7	5	1
3d	29.7/4.3	6	12	0	28.5	2	16.6	32.5	5	2
4a	29.7/4.3	3	12	0	30.1	1	8.3	28.0	7	3
4a10.2	70.3/10.2	12	12	0	30.1	0	0	1.0	n/a	n/a
4b	29.7/4.3	3	12	0	30.1	0	0	36.4	2	1
4c	29.7/4.3	3	12	0	30.1	0	0	18.7	4	1
4d	29.7/4.3	3	12	0	30.1	0	0	19.0	0	0
4e	29.7/4.3	3	12	0	30.1	0	0	18.0	4	1
4f	29.7/4.3	3	12	0	30.1	0	0	17.7	0	0
5a	29.7/4.3	6	19	19	31.5	4	10.5	28.5	11	4
5b	29.7/4.3	6	11	0	32.0	0	0	1.0	0	0
6	41.4/6.0	6	15	14	32.9	1	3.4	21.1	3	0
610.2	70.3/10.2	24	15	14	32.9	0	0	1.0	n/a	n/a
7a	44.8/6.5	3	11	0	28.2	4!!	36.3	25.6	8	6
7b	44.8/6.5	3	11	0	28.2	2	18.2	25.6	8	4
8a	44.8/6.5	3	29	11	32.4	7	17.5	25.6	20	13
8b	44.8/6.5	3	30	11	32.6	10!	24.4	25.5	22	17
9a	44.8/6.5	3	15	9	32.1	1	4.1	25.6	12	7
9b	44.8/6.5	3	14	9	33.8	2!	8.7	25.6	6	1
9c	29.7/4.3	3	9	2	34.8	3	27.3	25.6	5	4
9d	*29.7/4.3*	*3*	*6*	*1*	*36.4*	*0*	*0*	*24.7*	*2*	*0*
10	69.7/10.11	3	14	5	31.7	1	5.2	17.0	6	3
11a	29.7/4.3	4	16	12	33.2	3	10.7	38.5	9	4
11b	*44.8/6.5*	*2*	*1*	*3*	*39.5*	*0*	*0*	*18.2*	*1*	*0*

P2 is the ambient pressure in the altitude chamber. ! one case was classified as Type II DCS; !! 2 cases were classified as Type II DCS. n/a = not applicable; monitoring for VGE was not performed. Tests with fewer than ten subjects (*shown in italics*) were not used in the TBDM DCS Probability Model.

exercise and were just generally active and also slept during this period. The DT performed the same or longer PB as the subjects. The DT provided proper precordial placement of a Doppler ultrasound probe over the pulmonary artery of the subject during the intervals of VGE monitoring. After three 4-min exercise periods, the subjects would recline on a cot and for a 4-min interval the DT would maintain an optimal pulmonary artery blood flow signal so that the principal investigator could accurately score audio signals from the Doppler bubble detector on the Spencer 0–IV categorical scale. The details about the bubble monitoring are not the focus of this communication; however, we documented the number of any VGE grade and the subset number of Grade IV VGE per test in Table A1.

The number of subjects who participated in evaluating a prebreathe protocol ranged from 3 (Test 1d) to 41 (Test 8b). Some subjects participated in more than one test, but no subject participated more than once in a particular test. Subjects who developed DCS were removed from the test in accordance with test-termination criteria. Details of the 84 cases of DCS are available on request.

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