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

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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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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)