Biomedical and Technological Challenges of EVA

• **Decompression** (denitrogenation required to work in low pressure suit (4.3 psi))

• **Thermoregulation** (-120°C to + 120°C)

• **Nutrition** (200 kcal/hr requirement)

• **Hydration** (1 liter/EVA)

• **Waste Management**

• **Radiation**

• **Micrometeoroids and Orbital Debris**

• **Suit Trauma**

• **Mobility/Dexterity**: current pressurized suits reduce mobility and dexterity

• **Visibility**
Type II DCS – Percentage of All DCS vs. Diving Methods

- Character of Altitude DCS Different from Diving DCS
- Undersaturated Neurological Tissues
- “Softer Bubbles” Metabolic Gases

From DAN, 2005
Altitude DCS - Nitrogen Elimination during Oxygen Prebreathe

- Over 50% of nitrogen eliminated in first 30 minutes
- Brain, spinal cord Halftime ~ 5-10 minutes, muscle and skin halftimes
  - 15-25 minutes at resting conditions
- Resting prebreathe reaches point of diminishing return for reducing pain only DCS
- Type II DCS incidence higher on “Zero Prebreathe”

Shuttle Pre-breathe Ground Studies

Two Pre-breathe protocols approved for flight operation

- 4 hour in-suit resting oxygen pre-breathe
- 12 hr 10.2 psi staged decompression procedure
- R value (tissue tension (360)/suit pressure) = 1.65

Data on DCS and VGE incidence from 49 tests with n=925: mixed exposure times
Data on Grade 3 DCS incidence from 42 tests with n=689
Flight Experience Shuttle 10.2 psi Staged Protocol – Zero DCS

Theoretical Tissue Bubble growth as a function of 10.2 exposure time

Time at 10.2 psi prior to shuttle EVA

Diving in Space | National Aeronautics and Space Administration | Mike Gernhardt
Shuttle Prebreathe Ground Trials (~ 25% DCS, ~ 5% symptoms that would terminate an EVA.) Acceptable Risk?
- 4 hour prebreathe
- 10.2 psi staged protocol
- 146 EVAs exposures with no reports of DCS

Limitations
- Timeline, back to back EVAs,
- O2 usage, ISS O2 concentration
- Crew isolation and comfort

Duke, NASA micro-gravity simulation (non ambulation)
Enabling Research

Air Force Research Laboratory
Brooks AFB, Texas

Diving in Space | National Aeronautics and Space Administration | Mike Gernhardt

Exercise-Enhanced Preoxygenation Increases Protection From Decompression Sickness

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INTRODUCTION

Preoxygenation is the process of removing nitrogen from the tissues by breathing gas with a lower partial pressure of nitrogen than contained in the body fluids and tissues. Preoxygenation reduces the potential for nitrogen supersaturation and subsequent gas embolism formation during decompression. Breathing 100% oxygen prior to decompression (preoxygenation or pre-breathing) is a common method of preoxygenation to reduce the risk of DE (1). An improvement in decompression efficiency would have application in both the space program and high altitude aviation.

Decompression before extravehicular activity (EVA).

Preoxygenation reduces the risk of decompression sickness (DCS). The staged decompression procedure begins with 1 hr at 19.7 kPa oxygen (150 mm Hg PO2), equivalent to breathing atmospheric air at about 600 ft (180 m), followed by decompression of the entire Shuttle to 10.2 kPa for at least 12 hr while the crew breathes 25% oxygen (100 mm Hg PO2) equivalent to breathing atmospheric air at about 1200 ft (380 m), and then an additional 40-min period of breathing 100% oxygen at 10.2 kPa before decompression to 4.3 kPa. The staged decompression results in a 365-mm theoretical tissue hollow (166 mbar) of nitrogen (Final Tissue P50/Absolute Ambient Pressure) that is closer to the TE resulting from a 4-h hypoxemia (177 vs 165). However, the staged decompression is not without problems such as reduced instrument cooling capacity due to lower air density. Time-efficient preoxygenation techniques allowing decompression directly from 14.7 to 4.3 kPa while providing protection comparable to staged decompression would be preferable.

PO2 peak = 88% lower body, 12% upper body.
Prebreathe Reduction Program

- Start by defining acceptable DCS risk for ISS mission and developing accept/reject limits for countermeasure trials
- Early development focused on delivering acceptable/effective countermeasure
- Later development focused on increased efficiency and improved scientific understanding of countermeasure mechanisms

Prebreathe Reduction Laboratory Studies
- 5 Year Operational Research Plan

Acceptable DCS Risk Definition

- 2 Hr. Prebreathe Protocol
  - Phase 1 ✓
  - Phase 2 ✓
  - Phase 3 ✓
  - Phase 4 ✓

- 1.5 Hr. Insuit Prebreathe
  - Phase 5.1 **
  - Phase 5.2
  - Phase 5.3
  - Phase 5.4

- Relationship between Micro-g sim. and exercise

- Break in Prebreathe Studies
  - Phase 6.1
  - Phase 6.XX

- Supporting Studies
  - Brooks Studies *
  - adynamia cross over study
  - Cardiac Output
  - Blood flow
  - Nitrogen Elimination

Accept: DCS ≤ 15% and Grade IV VGE ≤ 20% , @ 95% C.l
Reject: DCS > 15% or Grade IV VGE > 20% , @ 70% C.l
Multi-Center Study: NASA, Duke, DCIEM, Hermann UT

2hr oxygen prebreathe

Exercise 10 mins @ 75% VO2_{peak}
And/or light exercise (160-253 Kcal/hr)

Micro-gravity simulation (non-ambulation)

Simulated EVA exposure at 4.3 psi 4 hrs

Use of “Suit Simulator” for EVA Exercise
Prebreathe Trials

- High intensity exercise (75% peak oxygen consumption [VO₂ peak])
- Low intensity activity (5.8 mL·kg⁻¹·min⁻¹ VO₂)
- Neither High or low intensity exercise was acceptable
- Coupling High with low intensity exercise was acceptable

PRP Phase I-IV 2 hr oxygen prebreathe exercise protocols

DCS and Grade IV VGE observations (shown with 95% upper confidence limit bars dashed lines indicating accept levels for DCS and VGE incidences)
Exercise and Inert Gas Kinetics

\[ P1N2 = P0 + (1 - \exp(-k1t)) \times (Pa - P0), \]

\[ k1 = \left( \frac{1}{\exp(-\lambda \cdot mL/kg^{-1} \cdot min^{-1})} \right) / 519.37 \].

Hosmer-Lemshow Goodness of fit statistic = 2.188 with 5 degrees of freedom, \( p = 0.82 \) (significance > .05)
Exercise Prebreathe Protocol: Experience to Date

- Overview - The exercise prebreathe protocol has been used successfully on 34 EVAs from the International Space Station (ISS) - no DCS
  - Five Shuttle assembly flights and two increment EVAs
    - Starting in July 2001
  - These assembly missions would have been difficult or impossible to execute as base-lined, without the protocol
A United States Airlock: Doorway to Space

U.S. “Quest” Airlock
The Challenge of Moving Past Apollo

- Apollo was a remarkable human achievement
- Fewer than 20 EVAs, maximum of three per mission
- Constellation Program, up to 2000 EVAs over the 10 year Lunar program
- Limited mobility, dexterity, center of gravity and other features of the suit required significant crew compensation to accomplish the objectives. It would not be feasible to perform the constellation EVAs using Apollo vintage designs
- The vision is to develop an EVA system that is low overhead and results in close to (or better than) one g shirt sleeve performance i.e. “A suit that is a pleasure to work in, one that you would want to go out and explore in on your day off”
- Lunar EVA will be very different from earth orbit EVA – a significant change in design and operational philosophies will be required to optimize suited human performance in lunar gravity
Challenges for EVA on the Moon

• Dealing with risk and consequences of a significant Solar Particle Event (SPE)

• Long duration missions with three 8hr EVAs per person per week
  – Apollo suits were used no more than 3 times
  – Individual crewmembers might perform up to 76 EVAs in a 6-month mission
  – Suit-induced trauma currently occurs with even minimal EVA time

• With Apollo style un-pressurized rover (UPR), exploration range is limited by EVA sortie time and 10 km walkback constraint
  – Science community input that optimal scientific return within this range could be accomplished within ~ 30 days of EVA
  – Two UPRs could extend exploration range up to 15-20 km (crew-day limited)

• Apollo highlighted the importance of dust control for future long duration missions

• Increased Decompression Sickness (DCS) risk and prebreathe requirements associated with 8 psi 32% O₂ cabin pressure versus Apollo with 5 psi 100% O₂

• The high frequency EVA associated with the projected lunar architectures will require significant increases in EVA work efficiency (EVA prep time/EVA time)
“The Wall of EVA”

ISS Construction (projected)

Year


EVA Hours

0 50 100 150 200 250

Gemini Apollo/Skylab Pre-Challenger Shuttle Shuttle
Available Lunar EVA Hours (LAT-2 Option 2) – based on Three 8 hour EVAs per week using Unpressurized Rovers

→ Need to extend range well beyond 10 km
Intermittent Recompression - Background

- Current plans for lunar surface exploration include Small Pressurized Rovers (SPRs) that are quickly ingressed and egressed with minimal loss of consumables.

- This capability enables crew members to perform multiple short extravehicular activities (EVAs) at different locations in a single day versus a single 8-hr EVA.

- Previous modeling work and empirical human and animal data indicate that the intermittent recompressions may reduce decompression stress.
Tissue Bubble Dynamics Model (TBDM)- Provides Significant Prediction and Fit of Diving and Altitude DCS Data

- Decompression stress index based on tissue bubble growth dynamics (Gernhardt, 1991)
- **Diving**: \( n = 6437 \) laboratory (430 DCS cases)
  - **Logistic Regression Analysis**: \( p < 0.01 \)
  - **Hosmer-Lemeshow Goodness of Fit** = 0.77
- **Altitude**: \( n = 345 \) (57 DCS, 143 VGE)
  - **Logistic Regression Analysis (DCS)**: \( p < 0.01 \)
  - **Logistic Regression Analysis (VGE)**: \( p < 0.01 \)
  - **Hosmer-Lemeshow Goodness of Fit (DCS)**: \( p = 0.35 \)
  - **Hosmer-Lemeshow Goodness of Fit (VGE)**: \( p = 0.55 \)

\[
\frac{dR}{dt} = \frac{\alpha D}{h(r,t)} \left( P_a - vt + \frac{2\gamma}{r} + \frac{4}{3} \pi r^3 M - P_{\text{Total}} - P_{\text{metabolic}} \right) + \frac{\gamma v}{3}
\]

\( t = \) Time (sec)
\( a = \) Gas Solubility ((mL gas)/(mL tissue))
\( D = \) Diffusion Coefficient (cm²/sec)
\( h(r,t) = \) Bubble Film Thickness (cm)
\( P_a = \) Initial Ambient Pressure (dyne/cm²)
\( v = \) Ascent/Descent Rate (dyne/cm²·cm)
\( g = \) Surface Tension (dyne/cm)
\( M = \) Tissue Modulus of Deformability (dyne/cm²·cm³)
\( P_{\text{Total}} = \) Total Inert Gas Tissue Tension (dyne/cm²)
\( P_{\text{metabolic}} = \) Total Metabolic Gas Tissue Tension

Intermittent Recompression - Background

• Intermittent recompression during saturation decompression was previously proposed as a method for decreasing decompression stress and time (Gernhardt, 1988)
  – Gas bubbles respond to changes in hydrostatic pressure on a time scale much faster than the tissues
• Intermittent recompression (IR) has been shown to decrease decompression stress in humans and animals (Pilmanis et al. 2002, Møllerløkken et al. 2007)

Discussion

A. One 2-h exposure, no preoxygenation

B. Diving in Space

Intermittent Recompression - 3 x 2hr EVA at 4.3 psi

**Bubble Growth Index (BGI)**

- 6hr Continuous EVA
- 0.5hr between 2hr EVAs
- 1hr between 2hr EVAs
- 2hr between 2hr EVAs
- 3hr between 2hr EVAs

**Time (hours)**

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Floating Through the Terminator in the Sea Space Continuum