Shallow Water Diving – The NASA Experience

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Standard NBL Dive

- Profile – 40 fsw for 240-390 min
- Breathing gas – nitrox (46% O₂)
- Dry suit (EMU) – pressurized to 4.2 psi
- Equivalent Air Depth of 23.2 fsw

*NBL - Neutral Buoyancy Laboratory, Johnson Space Center, Houston
*EMU - Extravehicular Mobility Unit (standard U.S. 'space suit')
## Pressure

Force per unit area

<table>
<thead>
<tr>
<th>ATA</th>
<th>FSW</th>
<th>PSI(G)</th>
<th>mmHg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>760</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>14.7</td>
<td>1520</td>
</tr>
<tr>
<td>2.2</td>
<td>40</td>
<td>26.7</td>
<td>1672</td>
</tr>
</tbody>
</table>

ATA – Atmospheres Absolute
FSW – Feet of Seawater
PSI – Pounds per Square Inch
mmHg – Millimeters of mercury
Boyles Law

At constant temperature, gas volume is inversely proportional to the absolute pressure

- As pressure increases, volume decreases
  - Breathing is a constant-volume process, the deeper the dive, the less breathing gas
  - Basis for treating arterial gas embolism (AGE), USN Table 6A

- As pressure decreases, volume increases
  - Cause of pulmonary barotrauma
  - Greatest risk of injury occurs near the surface
Henry’s Law

The amount of gas that will dissolve into a solution is directly proportional to the partial pressure of that gas.

- Deeper the dive, greater the gas load for each tissue.
- Upon ascent, gas in solution escapes to obtain equilibrium.
- Too rapid gas escape results in Decompression Sickness (DCS).
Shallow Water Diving

Adverse Physiologic Events

- Ear and Sinus Barotrauma
- Decompression Sickness (DCS)
- Pulmonary Barotrauma
  - Arterial Gas Embolism (AGE)
  - Mediastinal Emphysema
  - Subcutaneous Emphysema
  - Pneumothorax
- Oxygen Toxicity
Ear Barotrauma

- Problems can occur on ascent or descent
- Causes:
  - External canal obstruction – cerumen, earplugs, tight-fitting diving hood, congestion, otitis
  - Inadequate middle ear pressure equalization – URI, congestion/allergies, inadequate equalization

Unable to equalize if pressure >90 mmHg or 3.9 FSW
Ear Barotrauma

- **Symptoms**
  - Increasing pressure, then pain
  - Mild tinnitus and vertigo
  - Conductive hearing loss

- **Otoscopic Exam**
  - Grade 1 – TM retraction, diffuse erythema
  - Grade 2 – Slight hemorrhage within TM
  - Grade 3 – Gross hemorrhage within TM
  - Grade 4 – Bulging TM, fluid & blood in middle ear
  - Grade 5 – TM rupture, blood in canal
Ear Barotrauma

Grade 0

Grade 1

Grade 2

Grade 3

Grade 4

Grade 5
Ear Barotrauma

Treatment

- Treatment of pre-existing symptoms

- Avoid further diving until:
  - Pre-existing nasal symptoms have cleared
  - Diver can equalize pressure at surface
  - Complete resolution on otoscopic exam

- Long-acting topical nasal decongestants (Afrin)

- Systemic decongestants (Sudafed)
Sinus Barotrauma

- Problems can occur on ascent or descent
- **Causes:** Inflammation and congestion of nasal mucosa, structural deformities, mass lesions
- Chronic sinus disease – allergies, chronic irritation (smoking, nasal sprays), obstruction, vasomotor
Sinus Barotrauma

➢ Symptoms
  • Pain – frontal sinus most common
  • Epistaxis
  • Upper teeth pain
  • Infraorbital nerve – decreased sensation

➢ Treatment
  • No diving until symptoms resolved (7-14 days)
  • Long-acting topical nasal decongestants (Afrin)
  • Systemic decongestants (Sudafed)
Decompression Sickness

- Formation of bubbles in blood or tissue from dissolved inert gas (Nitrogen)

- Intravascular effects – platelet aggregation, leukocyte activation, increased cytokines, activation of complement, kinin and coagulation systems

- Rare occurrence in NBL divers
DCS Clinical Manifestations

Musculoskeletal – “Bends”

- Nitrogen bubbles in/around the joints
- Localized deep, dull, aching pain
- Primarily elbow, shoulder, hip, knee
DCS Clinical Manifestations

Cutaneous – Cutis Marmorata

- Transcutaneous bubble formation
- Cutaneous vascular injury
- Symptoms: intense puritis, mottling or marbling of skin
- Precursor to serious DCS
DCS Clinical Manifestations

Neurologic – Spinal Cord, Brain

- Spinal Cord – muscle weakness, paresthesias, paralysis, sensory loss
- May not follow typical nerve distribution
- Brain – headache, confusion, psychosis, LOC, profound fatigue, mental status changes
DCS Clinical Manifestations

Pulmonary – “Chokes”

- Nitrogen bubble obstruction of pulmonary vessels
- Requires severe decompression stress
- Occurs in 2% of DCS cases
- Symptoms:
  - Substernal burning pain
  - Paroxysmal cough
  - Shortness of breath
  - Aggravated by deep inspiration
DCS Clinical Manifestations

Vestibular – Inner ear

- Usually associated with deep mixed gas dives
- Symptoms
  - Vertigo
  - Tinnitus
  - Hearing loss
  - Nausea & Vomiting
  - Balance problems, “Staggers”
Decompression Sickness

Treatment

- 100% oxygen via aviator’s mask or anesthesia mask
- Hyperbaric oxygen therapy
- IV hydration
Pulmonary Barotrauma

- Excessive intrapulmonary pressure & over expansion of the lungs
- Breath holding or local pulmonary obstruction
- Out-of-air, panic, unfamiliar with equipment
- Rare occurrence in NBL divers
Clinical Manifestations

- Arterial Gas Embolism (AGE) – apnea, LOC, cardiac arrest
- Mediastinal Emphysema – substernal pain, cough
- Subcutaneous Emphysema – crepitus, hoarseness, dysphagia
- Pneumothorax

Treatment for AGE – CPR, 100% oxygen, recompression
Oxygen Toxicity

- Dependant on both the oxygen partial pressure and length of exposure

- Symptom onset accelerated by exercise

- Significant individual variability

- Acutely affects Central Nervous System (CNS)
CNS Oxygen Toxicity

- V - VISION; tunnel vision
- E - EARS; tinnitus
- N - NAUSEA
- T - TWITCHING; lips and facial muscles
- I - IRRITABILITY; includes anxiety, confusion
- D - DIZZINESS
- CONVULSIONS
## Oxygen Toxicity

NOAA Oxygen Partial Pressure & Exposure Time Limits

<table>
<thead>
<tr>
<th>Oxygen Partial Pressure in ATA</th>
<th>Max. Duration, Single Exposure (min.)</th>
<th>Max. Duration, Single Exposure (hr.)</th>
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<tr>
<td>1.6</td>
<td>45</td>
<td>0.75</td>
</tr>
<tr>
<td>1.5</td>
<td>120</td>
<td>2.00</td>
</tr>
<tr>
<td>1.4</td>
<td>150</td>
<td>2.50</td>
</tr>
<tr>
<td>1.3</td>
<td>180</td>
<td>3.00</td>
</tr>
<tr>
<td>1.2</td>
<td>210</td>
<td>3.50</td>
</tr>
<tr>
<td>1.1</td>
<td>240</td>
<td>4.00</td>
</tr>
<tr>
<td>1.0</td>
<td>300</td>
<td>5.00</td>
</tr>
<tr>
<td>0.9</td>
<td>360</td>
<td>6.00</td>
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<tr>
<td>0.8</td>
<td>450</td>
<td>7.50</td>
</tr>
<tr>
<td>0.7</td>
<td>570</td>
<td>9.50</td>
</tr>
<tr>
<td>0.6</td>
<td>720</td>
<td>12.00</td>
</tr>
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</table>
Oxygen Toxicity

- Astronaut training runs from 2004 – 2008
- 127 astronauts completed 2,231 runs for 12,880 exposure hours
- 57% of runs exceeded 6 hours
- 30% of runs, average depth greater than 20 FSW
- No cases of decompression sickness or oxygen toxicity
Oxygen Toxicity

17% exceeded NOAA Limits
Pulmonary Function In NBL Divers

- 43 working divers at NBL
- 1-2 90 minute dives daily, 40 FSW max depth
- Gas-54% nitrogen/46% oxygen
- Questionnaire – diving hx, smoking hx
- NBL dive hours – NBL database
- Medical records – height, weight, PFT for pre-dive, 1yr, and 3yr
Pulmonary Function In NBL Divers

Results

- Ave 340 dive hrs yr 1; 904 dive hrs yr 3
- No significant impact of pre-NBL dive exposure and diving outside NBL
- Initial lung volume (FVC & FEV1) greater than predicted (104% & 102%)
- Significant increase for both at 1 year & 3 years
- Correlation between NBL dive hrs & improved FVC/FEV1
- No change in small airway function
Pulmonary Function In NBL Divers

Conclusions

- Working divers more fit compared to general population
- Improved FVC/FEV1 supports adaptation to diving
  - Increased work of breathing
  - Respiratory muscle training
- No adverse effects of shallow Nitrox diving on small airway function
- Unknown contributory effect of 46% oxygen breathing gas
Hypothermia

- Hypothermia occurs even in warm water
- Water has a thermal conductivity 24 times greater than that of air
- 85 degree water has a 14 degree temperature gradient
- Most heat is lost in the water from the head and torso, not the extremities
- Physical activity without thermal protection will decrease body temperature by convection
<table>
<thead>
<tr>
<th>CORE TEMPERATURE (F)</th>
<th>SYMPTOMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>98</td>
<td>COLD SENSATIONS, SKIN VASOCONSTRICTION, INCREASED MUSCLE TONE, INCREASED OXYGEN CONSUMPTION</td>
</tr>
<tr>
<td>97</td>
<td>SPORADIC SHIVERING SUPPRESSED BY VOLUNTARY MOVEMENTS, GROSS SHIVERING IN BOUTS, FURTHER INCREASE IN OXYGEN CONSUMPTION, UNCONTROLLABLE SHIVERING</td>
</tr>
<tr>
<td>95</td>
<td>VOLUNTARY TOLERANCE LIMIT, MENTAL CONFUSION, IMPAIRMENT OF RATIONAL THOUGHT, POSSIBLE DROWNING, A DECREASED WILL TO STRUGGLE</td>
</tr>
</tbody>
</table>
Countermeasures

- Limit dive time to 90 – 120 minutes
- Wear wetsuits with an adequate thickness & proper fit – hood, gloves
- Replace old, worn-out suits that have lost thermal protection qualities
- Warm shower, warm fluids and warm dry clothing between dives
- Exercise
Flying after Diving

**DAN Recommendations:** Preflight surface interval of 12 hours for a single, no-decompression dive; and 18 hours for multiple dives per day or multiple days of diving.

**NASA Recommendations:** Cabin altitude 1,000 – 10,000 feet

<table>
<thead>
<tr>
<th>EAD (FSW)</th>
<th>No-Deco Limit (minutes)</th>
<th>Duration (min)</th>
<th>Air SI (hours)</th>
<th>Oxygen SI (minutes)</th>
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</thead>
<tbody>
<tr>
<td>0-20</td>
<td>No limit</td>
<td>1 – 60</td>
<td>3</td>
<td>20</td>
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<tr>
<td></td>
<td></td>
<td>61 – 100</td>
<td>5</td>
<td>40</td>
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<tr>
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<td>101 – 400</td>
<td>14</td>
<td>120</td>
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<tr>
<td></td>
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<td>&gt;400</td>
<td>24</td>
<td>180</td>
</tr>
<tr>
<td>20-25</td>
<td>400</td>
<td>1 – 45</td>
<td>3</td>
<td>20</td>
</tr>
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<td>40</td>
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<td>81 – 290</td>
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<td>120</td>
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<tr>
<td></td>
<td></td>
<td>291 – 400</td>
<td>24</td>
<td>180</td>
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QUESTIONS?