Modeling of Dissolution and Effervescence of Nitrogen Gas in Body Tissue and the Blood Stream

Analysis of the Cause of Decompression Sickness in SCUBA Diving

Master’s of Engineering in Mechanical Engineering
Master’s Project

Project Proposal

Andrew Goldfarb

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Abstract
Decompression Sickness (DCS) is a health risk of all SCUBA (self-contained underwater breathing apparatus) divers. DCS is caused by the effervescence of nitrogen in the divers bloodstream and body tissue; it can be extremely dangerous, even causing paralysis. If one follows the rules of diving, obeying the diving tables and ascent rates, the likelihood of getting DCS is low, but still occurs to many divers every year.

This project will analyze two facets of divers getting DCS – (1) judge the conservatism, for the diver not getting DCS, that exists in current dive tables using the standard ascent rate, and (2) create a table of maximum ascent rates, to be used in emergency situations, based on standard dive depths and durations, that should not result in the diver sustaining DCS.

Introduction / Background
SCUBA (self-contained underwater breathing apparatus) diving is an activity where one is able to descend beneath the water for extended lengths of time using compressed breathing air. People who SCUBA dive, both recreationally and commercially, are exposed to a variety of dangers. One of the major health risks which people are exposed to is Decompression Illness (DCI). DCI includes two conditions, Arterial Gas Embolisms (AGE) and Decompression Sickness (DCS).

AGE occurs when a bubble of gas is introduced into an artery, which can cause the stop of blood flow to the area supplied by the artery. AGE can be a very dangerous condition because the bubbles could prevent blood flow to portions brain causing the diver to go unconscious. The cause of AGE is typically lung overexpansion leading to lung rupture. The lung overexpansion is typically caused by a diver failing to exhale, as the breathing gas expands, during ascent, especially during a rapid ascent. This leads to the first rule of diving: don’t hold your breath and always breathe normally. If one follows this rule, AGE should not be a concern.

DCS, commonly known as “The Bends,” is caused effervescence, typically of nitrogen, in the bloodstream and in body tissue during a divers ascent to the surface, and when at the surface after a dive. When diving one breathes air at the ambient pressure of ones surroundings, if one is at a depth of 33 feet sea water (fsw) one is breathing air at 2 atmospheres. Because of the increased pressure of the breathing gas, body tissue absorbs excess nitrogen (due to the nitrogen’s increased partial pressure) thorough dissolution of the gas into body tissue. When a diver is at a constant pressure (at depth) the excess nitrogen is not harmful. However, when the diver ascends and the pressure on the body tissue is reduced, the nitrogen will expand and come out of body tissue. If a diver ascends at a moderate rate, the diver will off-gas the expanding nitrogen through exhalation, and no adverse health effects will exist. If a diver rises too quickly, the nitrogen will not be able to be off-gassed by the lungs quickly enough, and effervescence will occur in the bloodstream and body tissue. The effervescence of the nitrogen in the bloodstream and body tissue can be extremely dangerous causing extreme pain, and potentially paralysis. To avoid DCS SCUBA diving teaches one to always ascend at a moderate rate, no faster than 1 foot per second, and to always follow the appropriate diving tables, as shown in Figure 1, to ensure one does not off-gas nitrogen too quickly or have excess nitrogen dissolved in body tissue. The
ascent rate rule and diving tables have been designed to be conservative and are able to help reduce the risk of DCS in recreational diving. (Despite the conservativeness in the rules and tables, incidents with DCS still happen every year in commercial and recreational diving.)

Figure 1: Standard PADI Diving Table
Problem Description

The intent of this project is to create an analog model of human body tissue and to perform analysis of the diffusion, effervescence, and concentration of nitrogen in body tissue as the ambient pressure (depth), time at pressure (dive time), and ascent rate are varied. The model may then be used to validate points on standard dive tables, shown in Figure 1, to show that DCS would not occur. One desired outcome of the model would be to determine the maximum safe rate of ascent one can achieve during an emergency situation, without getting DCS, for nominal dive depths and durations (within the dive table limits).

Methodology / Approach

COMSOL Multiphysics will be used to create a computational fluid dynamic (CFD) analog model of human body tissue to allow for the analysis of the nitrogen diffusion, effervescence, and concentration. The mechanical properties the human body tissue will be based on an average body. In addition to the CFD analysis a transient form of Henry’s Law will be used through an analytical method to validate the CFD model created in COMSOL.

The first set of scenarios that will be performed utilizing the model will be to take points that exist along the dive table’s maximum depths and dive times with the standard ascent rate of 1 foot per second to ensure that the model does not indicate DCS. If DCS is indicated, the assumptions used in creating the model will need to be reevaluated and modified to ensure that when diving within the standard table and ascent rate, the model does not show DCS.

Once the model is validated analytically and shown to agree with standard dive tables, the model may then be used to create a table of maximum ascent rates for dives of specified depths (ranging from 40 fsw to 120 fsw in 20 foot intervals) and duration (ranging from 5 minutes to maximum dive time [per the standard table] in 5 minute intervals) that would not result in DCS.

Resources Required

- COMSOL Multiphysics
- Fluid Dynamics, Multiphase Flow, and Transport Phenomena Textbooks
- Mathworks MATLAB
- Microsoft Office Software Suite
- Physiological data of the typical human body (Nitrogen absorption and dissipation rate)
**Expected Outcomes**

It is expected that the outcomes will show that the standard dive tables are extremely conservative, and that effervescence is unlikely if diving within the tables, for all combinations of depth and time. This is the expected result as people SCUBA dive using standard tables everyday, and very few dives result in DCS.

It is also expected that the maximum rate of ascent that would not result in DCS will be in excess of the 1 foot per second guideline. This is expected because the guideline like the tables is designed to be conservative, and while designed as a maximum rate, divers frequently unintentionally exceeded this rate and do not sustain DCS. The table created by the analysis, after thorough vetting, will be a useful tool for SCUBA divers to us in emergency situations, when an ascent of 1 foot per a second is not possible.

**Milestones / Deadlines**

**Project Milestones:**

1) Complete Research ................................................................. 6/2/2013  
2) Complete Initial Modeling .................................................... 6/14/2013  
3) Complete Report Outline / Layout ........................................ 6/20/2013  
4) Complete Refined / Final Modeling ....................................... 7/1/2013  
5) Complete All Modeling Scenarios ......................................... 7/12/2013  
6) Complete Initial Report Draft ................................................ 7/17/2013  
7) Complete Report .................................................................. 7/25/2013

**Deadlines:**

1) Tentative Project Proposal Draft ............................................. 5/27/2013  
2) Project Proposal Draft .......................................................... 6/3/2013  
3) First Progress Report ............................................................ 6/17/2013  
4) Second Progress Report ....................................................... 7/8/2013  
5) Final Draft Report ............................................................... 7/22/2013  
7) Final Report ......................................................................... 8/5/2013
**References**


**Appropriate Journals for Potential Publication of Results**

- Alert Diver – The Magazine of the Divers Alert Network
- Diving and Hyperbaric Medicine Journal
- Undersea & Hyperbaric Medical Society Journal
- Additional journals to be determined