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PI Name:	Gerth, Wayne Ph.D.		
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PI Email:	wayne.a.gerth@navy.mil	**Fax:**	FY
PI Organization Type:	GOVERNMENT	**Phone:**	(850) 230-3100 3247
Organization Name:	Navy Experimental Diving Unit		
PI Address 1:	Department of Biomedical Research		
PI Address 2:	321 Bullfinch Road		
PI Web Page:			
City:	Panama City	**State:**	FL
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Contact Monitor:	Meck, J@n	**Contact Phone:**	281-244-5405
Contact Email:	janice.v.meck@nasa.gov		
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Task Description:

Astronauts are routinely exposed to atmospheric decompressions that incur significant risks of Decompression Sickness (DCS). These exposures occur during in flight Extravehicular Activity (EVA) and during ground-based operations that include EVA training exercises in neutral buoyancy facilities under hyperbaric conditions followed by flight in hypobaric aircraft cabins. Programmatic management of these risks requires: a) definition of risk/hazard envelopes for all routine and emergency decompressions that may be encountered by NASA training and flightcrew; b) quantitative consideration of the inclusion or introduction of such risks in the design, testing and implementation of new operational procedures and equipment, and; c) real-time monitoring of DCS risk incurred by personnel during various training and spaceflight operations. Proposed work will contribute to meeting these objectives through continued refinement and application of methods that allow DCS risks to be quantitatively estimated throughout the time courses of pressure/respired gas/time profiles of arbitrary complexity. The risks are computed as probabilistic functions of various properties of modeled DCS etiologic processes during the profiles, including in vivo gas exchange and bubble dynamics. These models now account for effects of exercise on the rates of compartmental blood-tissue gas exchange and the efficacy of oxygen pre-breathe, the effects of oxygen as a diffusible gas on bubble growth and resolution, vasoactive effects of oxygen, and how the profusion of bubbles in any given tissue is affected by the magnitude of the prevailing gas supersaturation. They have been successfully used to aid development of a reduced EVA prebreathe protocol, which has supported a total of 34 DCS-free EVAs from Space Station and Shuttle to date since first use on STS 104 in July 2001. Parameters in the models are optimized using maximum likelihood to ensure that the models provide their best-possible reproductions of experience in training data sets that consist of detailed descriptions of actual human decompressions and their observed DCS outcomes. Optimized models are then readily used to estimate DCS risks in particular profiles, or to compute prebreathe protocols and decompression schedules that explicitly limit DCS risk while minimizing time and materiel requirements. In proposed work, model training data sets will be expanded by addition of still-uncoded data from altitude, diving and flying-after-diving man-trials that have been completed at NASA, USAF Armstrong Laboratory and USN laboratories and their contractors. DCS incidence and time-of-occurrence models will be optimized about these expanded datasets and used to support continued development of reduced prebreathe time protocols for EVA in conjunction with the ISS DCS Risk Definition and Contingency Plan program at NASA-JSC. The models will also be used to integrate real-time precordial Doppler Venous Gas Emboli (VGE) data collected from EVA astronauts using the NASA-JSC In-Suit Doppler with previous experience to forward use of such information as a real-time premonitory index of DCS onset. Integrated system software for running the optimized models on personal computers will be packaged and delivered at conclusion of the program for evaluation and use by NASA personnel.

Rationale for HRP Directed Research:

Research Impact/Earth Benefits:

Task Progress:

A. Training data augmentation
The compilation of data from the NASA-JSC historical database of altitude tests is complete. The data are from eleven (11) chamber tests conducted at NASA-JSC between 1980 and 1995. They are tabulated in Excel spreadsheets, each sheet containing data from a single test protocol. The number of protocols per test varies from 1 to 6, with a total of 31 across the 11 tests. The data are from 237 subjects; 176 males and 61 females. The total number of altitude exposures is 549, of which 82 culminated in diagnosed cases of DCS and 467 were completed with no DCS. Thus, the overall DCS incidence in these exposures is 82/549 or 14.9%.

The spreadsheet data include information such as subject’s age, height, weight, body surface area, cholesterol level, and so on, as well as descriptions of the pressure, breathing gas, and exercise profiles for each exposure.

Data items specifically needed for present model development and testing were extracted from the spreadsheets into 31 Augmented NMRI (Navy Medical Research Institute) text format data files. Comments were inserted in each line of data for easy identification. From a modeling perspective, we now have accurately detailed machine-readable descriptions of the NASA-JSC exposure profiles, including oxygen pre-breathe time, exercise times and levels, and either the DCS onset time or the right-censored time (no symptoms by end of test) for each exposure. The data also include observations on grade (0 – IV Spencer scale) and onset time of venous gas emboli detected using a Doppler ultrasound instrument.

Data from more than 3322 hyperbaric man-exposures have also been augmented with appropriate information about exercise performed during the exposures. In most cases, the added information was obtained by review of original reports and Navy Experimental Diving Unit laboratory logbooks. These hyperbaric data have been combined with our altitude exposure data to develop a model that will be applicable to the full range of altitude, diving, and flying after diving exposures encountered by NASA personnel. Limited success of such models to date has long been suspected due to the different temporal distributions of exercise in typical altitude and diving exposures. Exercise tends to be performed after decompression in altitude exposures and before decompression in diving exposures. Without proper accommodation of this difference in a model or the data to which the model is fit, different exercise effects are averaged over the entire training data set with adverse impact on overall model fit and applicability.

B. Linearization schemes and parameter optimization

A new variable tissue volume model (VTVM) of tissue gas bubble dynamics has been developed that takes advantage of a linear scalability property of our gas and bubble dynamics equations. A scaled VTVM with arbitrary values of all model parameters except tissue volume produces a model equivalent to any unscaled VTVM model. A model of DCS incidence and time of occurrence based on the scaled VTVM is consequently fit to DCS data with linear optimization schemes that are much simpler than the nonlinear schemes required to fit unscaled models. The simplicity affords substantial reductions in the times required to optimize the model about any given training data set and in the times required to solve the optimized model to estimate DCS risks of new decompression exposures. As a result, the model promises great utility in application to real-time prescriptions of decompression schedules for exposures of arbitrary complexity.

Linear optimization procedures have been developed that provide fits of the scaled VTVM to collections of widely heterogeneous diving exposure profiles with goodness-of-fit measures comparable to those obtained for unscaled models optimized about the same data. However, the reliability of DCS risk estimates yielded by the fitted scaled models for profiles not within the training data has been poor compared with the reliability of estimates yielded for the same profiles by fitted unscaled models. Analytical modifications to the fitting and risk estimation procedures have been implemented to address this lack of reliability, but need further testing. At any rate, it is clear that any scaled VTVM model will require validation with an unscaled version optimized about the same training data. Our model development work is proceeding accordingly along two parallel paths; one in pursuit of a scaled VTVM and the other in pursuit of a corresponding unscaled version. Exercise effects on compartmental blood flow, oxygen content, inert gas exchange, and bubble nucleation have been incorporated into a fully elaborated VTVM, but have been tested only in the unscaled version.

C. Evaluation of newly parameterized model features.

1. Exercise versus VGE. Nonlinear optimizations of models based on the unscaled version of the fully elaborated VTVM have been attempted about expanded training data including both diving and altitude exposures. The focus of this effort has been on models that accommodate the influences of multiple inert gases and oxygen on bubble dynamics, with tissue O2 contents determined in accord with physiological Hb-O2 dissociation in the compartmental perfusate. Behavior of resultant models on the majority of profiles in the training data was consistent, but the solutions for select profiles, particularly those involving diving saturation exposures with long slow decompressions, was erratic. The erratic behavior was traced to numerical instabilities in our solutions for the coupled nonlinear differential equations that are required to deal with gas bubble dynamics (dr/dt), compartmental dissolved gas tensions (dpt/dt), Hb-O2 dissociation, bubble nucleation, and exercise effects on compartmental perfusion and oxygen content.

2. A new and efficient numerical procedure for solving the gas and bubble dynamics equations has recently been developed that promises to minimize or eliminate numerical instability. The procedure is semi-analytic in that it allows model state variables at the end of each successive small time interval to be computed directly from their values at the beginning of the interval. The procedure is readily applicable to bubble dynamics governed by exchanges of multiple diffusible gases between bubble and surrounding tissue. Model optimizations will resume when incorporation of this procedure into our otherwise fully-elaborated models is complete.

E. System Software

A prototype Planner for altitude, flying after diving, and diving exposures has been developed based on the graphical user interface of the U.S. Navy Thalmann Algorithm Dive Planner. The latter has been extensively tested and approved for operational use under waiver by select users in the U.S. Navy diving community. Unlike the Thalmann Algorithm Dive Planner, which is based on the deterministic neo-Haldanian Thalmann Algorithm, the new prototype Planner incorporates the much more complex and compute-intensive probabilistic gas and bubble dynamics models that are being developed in this and related work. The software structure of the prototype will allow ready incorporation of new models as they become available. Continued refinement is underway to improve the operational speed of the package.

[Ed. note 9/23/10: submitted by Task Book editor, from annual report sent by C. Guidry/JSC)

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