Summary

In the US Navy diving community there is an essential interdependence between the biomedical researcher, the engineer and the operator. Before operational capabilities can advance, biomedical research must define the nature of the biological events that accompany exposure to extreme environmental conditions. Based on the results of this research, the biomedical researcher and the engineer work together to develop specifications for diving equipment and systems, and the biomedical research scientist and operator work to develop procedures for use during diving operations. The engineer and operator often encounter problems in the course of their work for which they refer to the diving biomedical research community for elucidation, and hopefully, solution. Thus, the biomedical researcher, engineer and operator comprise a triad that is necessary for the advancement of operational capability. By their contributions, Navy biomedical researchers have enhanced substantially US Navy operational capabilities in the past 15 years. This paper will highlight some of these contributions and show the impact that they have had on the diving capability of the United States Navy.

Historically, the availability of suitable decompression schedules has posed the biggest constraint on US Navy Fleet Diving Operations. By late 1967 the US Navy had a subsaturation diving capability of 300–350 ft aboard its ASRs and ASBs. The Advanced Diving System (ADS) 4, a leased deck decompression chamber-personnel transfer capsule (DDC-PTC) system, provided some extension of capability to 450 ft. SEALABs I and II demonstrated the feasibility of saturation diving to depths of 220 ft. In early 1968, a 600-ft, 7-day, bottom-time dive was performed by SEALAB III personnel, the first dive of its sort of depth for 24 hr. The biomedical research conducted during this dive, and subsequently during deeper and longer dives throughout the next 10 years, extended the US Navy's saturation dive capability four to fivefold, making it consonant with the new ASR (USS PIGEON and USS CERATO) depth capability of 1000 ft. This work demonstrated the feasibility of diving to depths of 1500 ft, or more, and provided usable schedules for saturation decompression. Concurrent with this development, the introduction of unlimited saturation-exursion limits improved flexibility of saturation dive schedules. This development allowed either upward or downward jaunts of a certain distance from storage depth for unlimited periods of time. Decompression tables for various types of subsaturation diving have also advanced substantially. The introduction of new forms of underwater breathing apparatus, which involve breathing an inspired oxygen at constant partial pressure, necessitated the development of new decompression tables for this equipment. Consequently, decompression tables for use with the Mark XV and Mark XVI underwater breathing equipment were developed and are now being introduced into the Fleet.

To meet both immediate and long-term operational requirements we needed to formulate rational decompression schedules. Formulation of decompression schedules requires a rational understanding of the mechanisms governing inert gas transport in the human body. Therefore, research has focused on a systematic approach to the measurement and mathematical modeling of the physical and biological processes that underlie decompression. Research in the past decade has included the determination of the solubility of inert gases in body tissues and fluids, as well as a developing understanding of the factors that regulate bubble formation and growth during decompression. Navy researchers have developed a statistical description of inert gas exchange rates that avoids choosing between the assumption that decompression is dependent upon either perfusion or diffusion. This development has for the first time permitted the comparison of experimental and theoretical work in decompression between various groups of divers. The same group of researchers has developed a unified theory of decompression that combines the relative roles of blood perfusion, diffusion away from the capillary, diffusion parallel to the capillary and impedance of the capillary wall into a single mathematical treatment. This latter body of research is now serving as the basis for the calculation of new decompression schedules that are based on scientific fact rather than empiricism.

Not only have decompression procedures for returning to the surface from great depths been developed in the last 15 years, but also procedures for reaching great depths have been established. The high pressure nervous syndrome (HPNS), first observed in 1965, becomes prominent at depths near 500–600 ft. This syndrome involves primarily the central nervous system (CNS) and is manifest by incoordination, tremors, vertigo, nausea, disorientation and microsleep. It can have debilitating effects on diver effectiveness and safety. By slowing the rate in deep dives, however, the symptoms can be attenuated markedly. US Navy researchers in the last 15 years have developed compression schedules that virtually eliminate HPNS as a problem for the current operational diving capability of 1000 ft.

Other basic biomedical research conducted by US Navy investigators has added to our understanding of the basic pathophysiological processes that occur in HPNS. Pharmacological means of ameliorating this phenomenon have been developed. Taurine, a substance that is naturally occurring in the human body, has been shown to reduce markedly the severity of tremors and the electroencephalographic changes that are produced by exposure of animal models to very high pressures. This exciting discovery may potentially extend man's diving capability in the open sea to depths equivalent to 2000 ft.

Because completely safe decompression schedules have yet to be developed, the development of better methods to treat decompression sickness and cerebral air embolism has been a necessary concomitant. During decompression from saturation dives, variant forms of decompression sickness have been observed, especially those affecting the inner ear. Treatment guidelines
have been established for decompression sickness that occurs during saturation decompression. These guidelines specify the essential recompression required, the necessary time to spend at treatment depth, and the concentration of oxygen in treatment gas.

Considerable progress has occurred in the elucidation of the pathophysiological processes underlying cerebral air embolism and decompression sickness involving the central nervous system. This work, done in animal models, indicated that potentially fatal cardiac arrhythmias can result from cerebral air embolism, and that disturbances of cardiac rhythm are mediated by the brain and its nervous control of the heart. Additionally, Navy medical researchers have shown that after cerebral air embolism there is a massive outpouring of substances such as vasopressin, epinephrine and norepinephrine, which are potent vasoconstrictive agents and cause huge increases in arterial blood pressure. Pharmacological means to ameliorate the cardiac arrhythmias and rise in blood pressure have been developed. Therapeutic algorithms have been devised to treat the various disorders resulting from cerebral air embolism.

Our understanding of the mechanisms operant in decompression sickness that affect the central nervous system has progressed substantially in the last decade. We now know that the initial events in decompression sickness affecting the spinal cord are initiated by physicochemical interactions between bubbles of gas and blood, and that these interactions start a complex series of biochemical events wherein many pharmacologically potent substances are released. These substances, which are liberated in blood, then interact with damaged tissue and make it difficult for adequate blood flow to the tissue to be re-established. Navy researchers have shown that these events ultimately produce a situation in which the venous system draining blood away from the spinal cord is occluded, thereby preventing nutrient blood flow from reaching the spinal cord.

Research is underway to define the best depths and inspired oxygen concentrations for recompression therapy. Because recompression is not always curative, experimental work has sought to develop adjunctive pharmacological methods to enhance recovery and restore function. This work, which has been performed in animal models until recently, has now progressed to the point where clinical human trials are being conducted at the Bethesda Naval Hospital (Bethesda, MD) in patients with acute stroke.

Considerable research has been directed to the study of respiratory function in the diving environment. Diving operations and experimental work have demonstrated that breathing resistance in many types of underwater breathing equipment is excessive. This interacts with other factors such as immersion, dense gas and static pressures to hinder the diver's ventilatory performance and work capacity, and to hazard his safety. Navy investigators' research in the last 10 years has provided a better understanding of the response of the lungs and the respiratory muscles to these environmental factors. As part of this research, a noninvasive, nonresistant method was developed to accurately measure the pulmonary ventilation of working divers. This technique permits the fractionation of each breath into those contributions that the rib cage and the diaphragm/abdomen make, and is the pulmonary equivalent to an electrocardiogram.

This technique, coupled with other methodologies developed by Navy scientists, now allows researchers to measure the efficiency of the respiratory muscles under various conditions of loading. The results of this work have permitted us to better define the limits of resistance permissible in a diver's breathing equipment and to serve as the basis for the improved design and development of underwater breathing gear. To assist ventilation and gas exchange in divers, methods that enhance ventilation of the working diver have been examined. Navy investigators have shown that the respiratory muscles can be trained for both strength and endurance. This work serves as a basis for improving a diver's respiratory status, and is now also widely used for training the respiratory muscles of patients with various forms of chronic lung disease.

A promising technique that has been examined is the use of a high-frequency, low-volume ventilator that can be incorporated into a diver's breathing equipment to augment ventilation and gas exchange. These methods hopefully provide a means of circumventing the respiratory limitations of working at depths greater than 1000 ft.

Cold is pervasive in the diving environment. Where thermal drain occurs, the diver's performance is affected first and subsequently his safety may be jeopardized to the point where mere survival is at stake. The Navy's study of cold stress in diving has included several objectives. Firstly, this work has been determining the physiological events that occur in cold stress, and secondly, it has been determining the amount and distribution of heat needed to maintain a diver in an adequate, functional and safe condition. To obtain this information an assay of 13 pairs of heat flux sensors and thermistors are placed at various locations on one side of the diver's body. This system, which has been validated against whole body and regional calorimetry, provides measurements of whole body and regional heat loss in dry, high-pressure environments and during immersion.

Information derived from this system permits one to cite how much insulation and supplemental heat is required for all areas of the diver.

Navy biomedical researchers have shown that working divers breathing cold helium-oxygen in a euthermic environment at depth incur large losses of heat via the respiratory system. Based on these findings, the US Navy has required that the diver's breathing gas be heated during dives deeper than 500 ft. Research has determined the changes in lung function that occur while breathing either hot or cold gases. This research has provided criteria for safe minimal and maximal temperatures of breathing gases in the diving environment.

Navy biomedical researchers have achieved considerable progress in other areas in the last decade and a half. Examples are:

1. The demonstration that in the case of a set amount of pulmonary oxygen toxicity a greater amount of time must be spent in decompression.

2. The demonstration that corneal edema can result from diving with hard contact lenses. Subsequent Navy research showed that this problem can be circumvented by the use of soft lenses or fenestrated hard lenses.

3. The demonstration of the operational advantages and the physiological and performance limitations of one-atmosphere diving systems for Navy use.

4. The evaluation of the virulence and pathogenicity of common infectious disease agents of
man under hyperbaric conditions to insure that there was no untoward hazard.

(5) The development of a schema for safely administering anesthesia and drugs to an injured diver at depth.

(6) The demonstration that repeated exposures to the diving environment block the ventilatory response to carbon dioxide.

(7) The development of a device to safely transport injured UDT/SEAL team personnel back to safety under field conditions. Incorporated in this device were effective means of immobilizing injuries.

(8) The demonstration that in pregnant animals that developed decompression sickness, fetal development is thereafter normal if the decompression sickness is treated promptly and adequately.

(9) The demonstration that the time of onset of CNS oxygen toxicity in animal models can be prolonged markedly by administration of aspirin and nonsteroidal, or anti-inflammatory drugs.

(10) The development of a statistical means for predicting the mean time of onset and variance of CNS oxygen toxicity in various species.

The extraordinarily large and diverse research efforts summarized in this paper have provided answers and solutions to major operational problems in diving and have advanced markedly the operational diving capability of the US Navy. Excellent basic science and elucidation of mechanisms are fundamental prerequisites to the development of solutions to Fleet problems. There have been considerable spin-offs of this research in many areas of clinical medicine that are far afield of diving. Examples of these areas are the improved monitoring of critically ill patients as well as improved methods for treatment of stroke and spinal cord injury.

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