EXPERIMENTAL APPROACHES TO PROBLEMS OF THE HEART AND LUNGS IN DIVING

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Summary

Divers face problems during their work due to stresses placed upon the respiratory system by the hyperbaric environment. In addition, both the respiratory and cardiovascular systems may be injured during the course of decompression sickness. Work at the Naval Medical Research Institute (NMRI) is directed toward solving problems in both these areas. A system of magnetometers allows evaluation of the impact of stresses from the underwater environment on the diver's respiratory system without interfering with his breathing. Other research described herein is exploring high-frequency oscillation (HFO) of a diver's breathing gas as a means of lessening limitations imposed by increased gas density. Finally, recent and ongoing research described in this paper is aimed at understanding the nature and mechanisms of injury to the heart and lungs during decompression sickness, with the goal of improving prevention and treatment of this disorder.

Divers working at depth incur a limitation on their exercise performance that is imposed by the respiratory system. This limitation can be magnified by breathing equipment designed without regard for the unique stresses placed upon the respiratory system by the diver's environment.

To study the effects of the hyperbaric environment on the respiratory system, a system of magnetometers has been developed that allows monitoring of the diver's ventilation without interfering with his breathing, and without concern for the dependence on density of standard flow measuring devices.

A magnetometer consists of a pair of wire coils. Alternating current is passed through one of the coils. This induces a current in the second coil that is proportional to the distance between the coils. Using magnetometers to measure the anteroposterior (AP) and lateral (L) dimensions of the abdomen (ab) and rib cage (rc), Robertson et al. were able to calculate respiratory volume. The method was automated off-line using a digital computer and the following model for calculating pulmonary volume (V):

\[ V = (K1)(Arc) - (K2)(Arc)/(Aab) - (K3) \]

(1)

where (Arc) is the area of the rib cage and (Aab) is the area of the abdomen calculated by assuming a horizontal oval through the abdomen and chest, it is possible to isolate the actions of the musculature of the rib cage, the diaphragm, and the abdominal wall. Through other techniques, it is also possible to measure the oxygen cost of breathing. This is a measure of the amount of energy required to accomplish a particular respiratory effort. Knowledge about the actions of various muscle groups used during ventilation, when combined with information on energy expenditure, makes it possible to measure with great accuracy the effect of varying types of equipment on divers under a variety of conditions. New standards for diving equipment will eventually be based on measurements of this type.

The current on-line real-time method uses the four-pair magnetometer method proposed by Robertson et al. The system was implemented on a Digital Equipment Corporation PDP-11/03 computer under the RT-11 operating system. All programs were written in Fortran.

The data collected from the magnetometers and processed by a PDP 11/03 computer, allow the separate measurement of volume changes of the rib cage and the abdomen. Along with measures of gastric and esophageal pressures, the contribution of both the rib cage and the abdomen to the total work of breathing can be determined.

The major muscle of respiration, the diaphragm, operates most efficiently at a given length. The length seems to be that which is attained at the end of a normal, quiet inspiration. During exercise, the end-inspiratory lung volume increases as the level of exercise increases, apparently due to increases in rib cage excursion. This action helps keep diaphragm length at its optimum at all times.

During immersion, however, the carefully balanced system for assuring efficient respiratory motion is upset by hydrostatic pressure gradients, which in turn vary with body position. The chest wall becomes distorted, and this distortion results in loss of efficiency. Other factors involved in the disruption of the system are the presence of underwater breathing apparatus and increased gas density.

Using four pairs of magnetometers covering the abdomen and chest, it is possible to isolate the actions of the musculature of the rib cage, the diaphragm, and the abdominal wall. Through other techniques, it is also possible to measure the oxygen cost of breathing. This is a measure of the amount of energy required to accomplish a particular respiratory effort. Knowledge about the actions of various muscle groups used during ventilation, when combined with information on energy expenditure, makes it possible to measure with great accuracy the effect of varying types of equipment on divers under a variety of conditions. New standards for diving equipment will eventually be based on measurements of this type.

Other work has been directed at overcoming the respiratory limitation to exercise at depth. In animals, the uptake of O₂ and the elimination of CO₂ can occur in the absence of "breathing" if the gas in the animal's respiratory tract is oscillated at 10-50 Hz. Researchers at NMRI are exploring oscillation of breathing gas as a means of assisting the ventilation of divers during periods of severe hypoventilation and respiratory distress.

Hypoventilation occurs when divers slow their breathing to reduce the effort of breathing a dense gas. As a result, some CO₂ is retained in the blood rather than exhaled. This is particularly noticeable...
during exercise and can adversely affect susceptibility to decompression sickness. 3,4

Although many designs exist for effective high-frequency oscillators, the Navy is particularly interested in two designs. One vibrates the chest wall, and the other oscillates gas in the airways with small jets of compressed gas. The latter device could in theory be powered by a diver's compressed gas supply.

The HFO devices currently being tested in the clinical environment are not applicable to the diving situation. They are used on anesthetized patients with air or oxygen being delivered to the patient through an endotracheal tube. The first task NMRI investigators faced was to see if HFO could improve gas exchange if the constant flow of gas to a subject's upper airways was replaced by the subject's own breathing. As described below, we found that HFO did improve gas exchange.

Anesthetized dogs were placed in a box that acted as a negative pressure respirator (similar to the "Iron Lungs" of the polio era). The animal's airways were connected to an endotracheal tube that passed through the walls of the box and allowed the animal to breathe room air. The box surrounding the animal's chest was periodically evacuated, forcing the animal's lungs to expand and fill with room air. When the pressure in the box was returned to normal, the animal's lungs emptied; the pattern of breathing resembled normal inspiration. Blood samples were taken occasionally to insure that normal gas exchange could be maintained. To simulate the type of hyperventilation common in diving, the tidal volume generated by the respirator was reduced. As a result, the O₂ content in the blood dropped and CO₂ rose to new, stable levels. We then superimposed the oscillations generated by a very high-frequency jet ventilator (15-20 Hz) on tidal breathing. As a result, gas exchange was improved: the level of O₂ increased and the level of CO₂ decreased.

The second task NMRI investigators faced was determining whether the superposition of HFO on normal breathing would improve gas exchange during dense gas breathing. To determine this, investigators had animals breathe a mixture of 80% SF₆ and 20% O₂ instead of room air. The density of this mixture is 4.1 times the density of air at 1 ATM. This did not affect the ability of HFO to correct hyperventilation, however. Other investigators have found that the inhalation of 80% He- 20% O₂ does not influence the beneficial effect of HFO either. The relative insensitivity of HFO to gas density is good news to those studying the potential use of HFO in diving. This fact, moreover, also provides considerable insight into the mechanism of HFO, a mechanism in which "dead space" plays an important role.

A large part of each normal breath goes directly to the alveoli where gas exchange occurs. A significant portion, however, remains in airways and takes no part in gas exchange. This portion of the breath is referred to as dead space ventilation. Dead space is not fixed; the greater the amount of mixing between alveolar and airway gas, the less the dead space. It appears that HFO acts by increasing gas mixing and decreasing dead space. As a result, a greater portion of each inspired breath contributes to gas exchange.

Research is presently underway to study the effect of compressed atmospheres on HFO, both in animals and in divers. The human work does not involve tracheal intubation, and will closely follow expected conditions in real working environments.

In other work at NMRI investigators have been exploring heart and lung responses after decompression and during the course of decompression sickness. A variety of observations suggest that the lungs should be a major target organ for decompression-induced injury. It is generally accepted that decompression sickness results from the formation of bubbles or products of blood-bubble interactions during or after decompression. These bubbles or products may produce local circulatory obstruction or may act as emboli, traveling with blood flow to damage the circulatory system. The potential types of emboli include more than simple gas bubbles. Older work from bubble oxygenators formerly used during cardiopulmonary bypass operations has shown that bubbling gas through blood can denature plasma lipoproteins, thereby releasing bound lipid that may then coalesce into globules. 3, 4 In addition, gas bubbles in the blood act as foreign surfaces and may trigger a number of enzyme systems in the blood, causing activation of clotting proteins or platelets. 5, 6 Some experimental work suggests that as a result of such activation, bubbles may become coated with a layer of lipid to which platelets adhere. 7 Thus, in addition to simple gas bubbles, other emboli that may be present in blood during decompression or decompression sickness include lipid globules and semiparticulate emboli consisting of complexes of gas bubbles, lipid and platelets.

Because the inert gas partial pressure is always higher in venous blood than in arterial blood during decompression, gas bubbles tend to form first in venous blood. From an anatomical viewpoint, therefore, the lung should be a major target organ for decompression-induced injury since it receives essentially all of the venous blood in the body. Because the diameters of pulmonary capillaries are in the range of 10 µm, the lungs act as a filter for the various types of emboli that may be liberated during decompression.

Doppler studies have tended to substantiate these theoretical considerations. In both men and in unanesthetized sheep, Doppler recordings have suggested the occurrence of pulmonary bubble emboli in asymptomatic individuals following decompression from raised environmental pressure. 8, 9

Embolization of the lung following decompression by bubbles, lipid emboli and platelet aggregates is similar in some ways to more common types of embolic disease. It is especially similar to the embolization of blood clots to the lung (autologous thromboembolism), a common occurrence in hospitalized patients. In both instances, obstruction of the pulmonary vasculature causes a mechanical increase in pulmonary vascular resistance. A reactive increase in pulmonary vascular resistance also occurs due to vasoconstriction mediated by vasoactive substances that are blood-borne and released locally. Many vasoactive substances may also increase pulmonary vascular permeability. 10

We hypothesized that these changes in the lung might cause measurable alterations in lung function tests in men who were otherwise asymptomatic following deep air dives. To test this hypothesis, we performed two series of experiments. In each case men were studied after a recompression chamber air-dive to 285
In a separate study of men following a 285-fsw, 10-min air dives, measurements were made of forced expiratory flows, flow volume loops and closing volumes. They were made predive and at ½, 1, 3, 4 and 5 hr after the dive. The closing volume technique is considered a fairly sensitive indicator of small airways dysfunction in the lung. As small airways become injured by edema, spasm, or other disease processes, they tend to close during expiration at progressively higher lung volumes. This type of abnormality is reflected in an increase in closing volume. Analysis of closing volume data following the 285-fsw air dive demonstrated an increase in closing volume of 10% immediately postdive and of 16% at ½ and 1 hr postdive. At 2 and 3 hr, closing volumes were close to predive values, but increased more than 25% at 4 and 5 hr postdive. The initial increase in closing volume may represent smooth muscle spasm, while the later increase at 4 and 5 hr may result from shifts of fluid into the pulmonary interstitium, with the development of clinically silent, interceded lung water. Thus, while gross tests of the respiratory system were made of forced expiratory flows, flow volume loops and closing volumes, pulmonary resistance and pulmonary compliance. Precordial Doppler recordings were also made. The preliminary results of these measurements suggested that despite Doppler evidence of pulmonary bubble emboli in most subjects, the gross mechanical properties of the lungs remained unchanged.

The significance of these findings is twofold. First, the abnormalities in closing volume substantiate other evidence derived from animal studies that indicate that abnormal accumulations of lung water are an integral part of the mechanism of decompression-induced lung injury. Secondly, these findings show that tests which directly or indirectly measure increases in lung water may be useful indicators of decompression-induced injury before divers actually develop symptoms of decompression sickness.

The second point is especially important because one of the major biomedical problems in current diving practice is the development of safe, efficient decompression tables to meet new needs or the improvement of older tables already in use. Despite more than half a century of decompression research, it is still not possible to develop new tables without subjecting them to empirical modifications based upon the outcome of human testing. Such testing often causes many cases of decompression sickness, some of which are serious. It would be very useful to have an indicator of decompression-induced injury other than clinical illness to use in tests to develop new decompression tables. Our research suggests that tests that measure increases in lung water may provide such a tool.

Other work in HBO2 laboratories has been directed at understanding the more extreme end of decompression stress, namely decompression sickness. The clinical syndrome of "chokes" provides another illustration of the central location of the lung as a target in decompression sickness. "Chokes" (or pulmonary decompression sickness) is a manifestation of decompression sickness in the lung and has three symptoms: substernal pain, cough, and dyspnea or respiratory distress. The substernal pain associated with pulmonary decompression sickness is usually a burning pain that increases in severity with time. At onset, the pain may occur only during coughing, but as the disease progresses the pain occurs during inspiration and expiration as well. Initially, coughing is intermittent and readily provoked by cigarette smoking. As the disease progresses, however, paroxysms of coughing become uncontrollable. Dyspnea and the symptoms of respiratory distress increase progressively as the cough increases. Shock often accompanies the respiratory symptoms of "chokes." If untreated, pulmonary decompression sickness may be fatal.

In an early observation of a human case of altitude decompression sickness, Ferris and Engle described a "fiery red" appearance in the membranes of the throat. This observation, coupled with the fact that the symptoms of pulmonary decompression sickness in many ways resemble those of acute bronchitis, led us to speculate that the fundamental alteration of lung during decompression sickness might be acute inflammation of the mucosal linings of the bronchial tree. To investigate this hypothesis, we performed a series of animal studies in which the response of the lung was examined during severe decompression sickness. We used a variety of techniques, including bronchoscopy, measurements of arterial blood gases, measurements of the mechanical properties of the lung and pathological examination of lung tissue. The results of this work show that although airway dysfunction does occur in decompression sickness, it is a secondary rather than a primary effect. The most regularly occurring abnormalities in the lung during decompression sickness are increases in pulmonary artery pressures and pulmonary vascular resistance, falls in systemic blood pressure, loss of plasma volume with hemoconcentration, and falls in arterial oxygen, arterial carbon dioxide and arterial pH. The primary abnormality underlying these effects seems to be injury to the pulmonary vasculature by bubble emboli. This injury to the pulmonary vasculature causes the pulmonary vessels to leak, resulting in abnormal increases in lung water. This type of reaction in the lung has been seen in many serious diseases, such as overwhelming infection, shock, and has sometimes been referred to as "shock lung." Our work indicates that the response of the lung in decompression sickness has many features common to the "shock lung" state.

We are also interested in the types of injury that the heart may sustain during decompression sickness. Preliminary results from recent studies suggest that true heart failure is uncommon during severe decompression sickness. In some cases, however, a pattern resembling a myocardial infarction (heart attack) may occur. The pattern is presumably the result of obstruction of the coronary arteries by bubbles or by the product of blood-bubble interactions. If this pattern occurs and is left untreated, it is associated with a markedly shortened survival time.
This work will lead to improved means of prevention and treatment of decompression sickness.

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