The Physiology and Medicine of Diving

and Compressed Air Work

EDITED BY

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FOREWORD

The Changing Face of Diving Physiology

C. J. LAMBERTSEN

These are times when it appears that diving physiology and practical diving are breaking out of a long, long period of acclimatization and are at last preparing for extension to the limits of human tolerance. There are scientific and operational 'Everests' to be assaulted, and the assaults are long overdue. Divers have probed the seas for a thousand years, satisfied with reaching the shallows, not overtly concerned with advance of their art. Investigators have probed the chemical, the physical and the physiological effects of pressure and gases, simulating considerably greater depths than the practical diver has been willing to attain in the sea. Now, and especially during the past six years, a major change has occurred: interest in effecting progress in diving depth and duration has been strongly aroused in industrial and naval leaders, who wish to use divers for important practical work at depths several times greater than the plateau of performance which had for several decades been considered adequate by these same groups. The dominant bases for interest are the search for energy in the form of oil, and the requirement for development of salvage capability at great depths. The steady pressure to extend scientific exploration of this planet has also at last begun to have considerable influence.

As greater depths are probed, the scope of diving has also been expanding. Active interest is focused, not only upon classical air-diving and deep helium–oxygen diving, but upon the breath-holding diver, self-contained helium or nitrogen mixed-gas diving, pure oxygen diving, saturation and excursion diving methods, diving from submersible craft and the use of submerged habitats to facilitate maximum extension of depth or to attain extreme extension of duration in shallow exposures. It is becoming generally evident that it is not sensible to concentrate exclusively upon any one of these approaches, since each method will continue to be important indefinitely, and there will emerge the use of special gas mixtures as yet untried. In extending each situation, special problems are generated not only by depth and the gases breathed, but by the exact nature of the equipment used.

At present it is again the scientist who lags behind as men work and dive at depths still poorly studied, using almost in full the available basic information upon which further advance must depend. However, the oscillations of attention from practical to scientific accomplishment are increasing in frequency—from decades, to years, to months—and it should soon be possible to blend these into a phase of tight and fruitful collaboration between science and operations.

Such collaboration is vital if the problems presented to modern diving are to be overcome. As so ably described in this volume, the high pressure, cold, dark, turbid, wet, dense and buoyant undersea environment imposes gross limitations upon human performance. The stresses are physical as well as chemical, and they exist in the natural working state as well as in conditions of accident or intoxication. Communication of information from diver to diver by vision and hearing are impaired. The current, the viscosity and even the buoyancy of water restrict mobility and increase energy expenditure, as does the low water temperature. There still remains, with increasing rather than diminishing importance, need for understanding and means for overcoming the limitations imposed by decompression, by narcosis, by oxygen toxicity and by difficult pulmonary ventilation. It is even probable that limits may be imposed by hydrostatic effects, and certainly time presents the ultimate obstacle in any circumstance of physiological stress.

These and other effects, as for a variety of the physiological stresses imposed by space flight, are not independent. Extremely complex interactions of factors vary with depth, with exposure duration and with the method of diving employed.

A single example of the tremendously interesting but troublesome physiological interactions at great depth is represented by the narcosis which, produced primarily by inert gas effects upon central nervous system function, can reduce the diver to ineffectiveness and unconsciousness. The narcosis is potentiated by oxygen, carbon dioxide and of course by any lowering of deep body temperature. The inefficient mobility of the diver increases carbon dioxide production per unit of useful work. At the same time an increased airway resistance exaggerates respiratory work, limits alveolar ventilation and furthers the autointoxication by carbon dioxide which grossly deepens the narcotic influence of the inert gas. These factors (exercise, narcosis, alveolar hypoventilation and carbon dioxide retention) similarly interact to exaggerate oxygen toxicity.

These are attractive fields for quantitative physiological exploration, but are at the same time imposing obstacles to extension of practical diving.

Approaches to solving these problems have taken two important paths, each heavily dependent upon the design and construction of large and expensive equipment. One approach is extension of fundamental and applied research through the development of new pressure laboratories which simulate the wide range of conditions encountered in undersea work. It is to be hoped that out of such units will come results in part as informative as those of Bert, of Haldane and other pioneers in this field. From this point on it is quantitation of physiological disturbances that is required, as in current attempts to define the degree of narcotic impairment of various human abilities when the 'dose' of an inert gas is increased, which show that a narcotized diver can still hear and can see, at depths where he cannot remember what he went down for, cannot deduce the nature of the tasks and has lost the neuromuscular coordination required for the needed manipulation.

Quantitative studies are similarly necessary to define the limits of tolerance of various organs and tissues to the supranormal oxygen pressures which provide such benefit in shortening decompression.

The work of these laboratories can now be aided by appropriate use of modern computers, which can rapidly solve problems of decompression theory and experiment and can extend them to include the influences of alternation of inert gases or fluctuation of high and low oxygen levels.

Such studies, along with extensive and meticulous chemical and physiological investigations on animals are one path of progress. Attempts to circumvent physiological limitations upon diving have led also to new diving concepts and extensive engineering development, providing methods for work in the open sea. The deep diver, once required to hang on his stage for many hours of decompression after each descent, has had his range and effectiveness extended by saturation diving, with, after each descent, a single decompression after days or weeks of undersea work. Additionally, the diver now can descend to his work site in a pressure compartment, use it or a submerged habitat as a work station, then can be brought back to the surface, still under pressure, to effect his long decompression after pressurized transfer to the relative comfort of a large, surface decompression chamber. These supporting systems are very recent in the evolution of manned undersea activity. While they provide marked improvement in effectiveness, in safety and in comfort of the overall diving operation, the eventual performance of specific useful work is normally still carried out by an individual diver who leaves the relative comfort and safety of the submerged compartment, enters the water and breathes his gases at the existing ambient pressure, to bring his energy, skill and judgement to bear upon the task at hand. It is with the information upon which continuation and extension of this direct manned activity depends that the chapters in this volume are concerned.

PREFACE

Although robots or manned submersibles may be necessary for work at very great depths, so far as continental shelf depths are concerned, man himself will continue to be the cheapest and most versatile means of executing the many tasks required underwater for the foreseeable future.

The fund of knowledge on the physiological and medical problems that occur when man is exposed to a high-pressure environment has steadily increased over the past century. The pace in the last five years, however, has quickened considerably with the appreciation of the enormous potential to be found beneath the oceans. Much of this sudden surge can be attributed to the rapid expansion of the off-shore oil and gas industry and growing defence interests.

From time to time since 1955, the proceedings of symposia have been published at which current results and achievements have been discussed. However, we believe the time is now overdue for a more comprehensive review of the biomedical problems of life at high pressures. It is the purpose of this volume to summarize, in a form convenient for reference, the present state of knowledge in this area.

This volume is therefore an edited collection of reviews each written by an internationally recognized authority. As in any subject, where knowledge is incomplete, there are some areas in which there are a number of diverse hypotheses. Care has been taken to ensure that as many different views as possible are represented and thus some overlap and several conflicting arguments will be found. This is considered to be an important feature of this book. It is only by considering and evaluating each of these differing opinions that the student may be directed towards a thorough understanding of the relevant issues.

We have attempted in this volume to emphasize the biological problems affecting man at raised environmental pressures. However, where the interaction of human factors and engineering requirements are significant, such as with work in tunnels or caissons and the design of underwater breathing apparatus, authors experienced in engineering have also contributed. A few problems have been excluded intentionally; in particular, the provision of heat sources vital for keeping the deep diver warm. This is primarily a design problem, involving the commercial development of diving suits heated by either hot water, electrical or other means. Essentially practical elements of diving have also been excluded, such as the design and operation of submersible pressure chambers capable of mating to deck decompression chambers or submarines with lock-out facilities.

With so many disciplines and authors involved, every effort has been made to facilitate understanding by the reader. Whenever possible abbreviations are carefully explained. Respiratory abbreviations and symbols follow the recommendations in *Fed. Proc.* **9**, 602–605 (1950). The units for pressure are a particular problem, as no international usage has yet evolved. We have decided to use atmospheres as the primary standard and therefore throughout the text conversions have been made so that all the pressures are also given in atmospheres absolute (ATA).

The pressure of one atmosphere is considered to be equivalent to 14·696 pounds per square inch (psi : $\mathrm{lb/in^2}$) and 1·033 kilograms per square centimetre ($\mathrm{Kg/cm^2}$) and to the pressure exerted by 33·899 feet of fresh water or, assuming a specific gravity of 1·025, by 33·072 feet or 10·08 metres of sea water.

The physiological and medical problems of the two complementary fields of diving and of work in compressed air have been covered as comprehensively as the limits of a volume of this size permit. Although aviation physiology has not been included specifically, it is important to remember the valuable exchange of ideas that has occurred between workers in hypobaric and hyperbaric research. The present state of knowledge in aviation medicine has been effectively summarized in several recent textbooks. It is hoped this volume will be of similar value, not only to those who are interested in the effects of raised environmental pressures but also to those who work in related fields.

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Grateful acknowledgements to many other sources for permission to reproduce the numerous figures and tables in this volume are made by the contributors and a considerable effort has been made to ensure that, where not original, reference has been made to the source of each illustration. Any omission of the appropriate reference in the text is unintentional and it is hoped that, should it have occurred, the author or publisher concerned will accept this apology.

Acknowledgements and thanks are also due to the French Navy for permission to publish details of the DC55 constant ratio breathing apparatus.

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The opinions or assertions contained herein are the private ones of the various authors and are not to be construed as official or reflecting the views of the Naval Department of any nation or of any Naval Service at large.

Decompression and Therapeutic tables are given for the purposes of illustration and are to be used in accordance with accepted diving practice as given in the Standard Diving Manuals.

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The Compressed Air Environment

A. F. HAXTON & H. E. WHYTE

There is little doubt that the diving bell was the first practical means whereby men engaged on engineering construction were enabled to perform their tasks under water in a compressed air environment. The first recorded use of a pressurized diving bell is by Smeaton while repairing the foundations of a bridge over the River Tyne at Hexham in 1778. In 1819 Augustus Siebe invented the supply of pressurized air to a diving dress.

The technique of using compressed air in tunnels and caissons to balance the pressure of water in the subsoil and thus to exclude it from the workings was first conceived and patented by Sir Thomas Cochrane in 1830. The basic principle of Cochrane's patent constitutes, in effect, the modern air lock to be described later. The method was used intermittently from 1839 onwards for shaft-sinking and caisson work but it was not until 1879, when compressed air tunnels were being driven simultaneously in Antwerp under the Scheldt and in New York under the Hudson River, that it began to be used extensively for tunnelling. The first medical lock was used by the late Sir Ernest Moir in the same Hudson River Tunnel in 1889.

Since then the basic principles have remained unaltered and improvements in use have been confined to details in application. Some modern research, for instance, has been devoted to the practicability of keeping workers in a raised environmental pressure for periods extending to days, weeks and even months, with a view to holding men available for work at all times and gaining an overall saving in decompression time. Whilst prolonged immersion of this nature has been proved possible it is unlikely that civilian workmen will ever readily accept conditions whereby during their 24-hour day they are deprived of social and family contacts in a normal atmospheric environment.

This chapter is therefore compiled against a background of normal shift-work with a regular daily return to atmospheric conditions.