DIVING SCIENCES

OXYGEN DIVING

RYSZARD KŁOS

CRC Press
Taylor & Francis Group

Oxygen Diving

The book provides a derivation of the models used for calculating the risk and hazard of central oxygen toxicity pertaining to diving-based studies consistent with the research conducted earlier by the Royal Navy and the US Navy. This book forms the basis for extending the possibility of undertaking nitrox dives in combination with oxygen dives, thus significantly increasing tactical capabilities of conducting diving special operations.

Features:

- provides derivation of the models used for calculating the risk and hazard of central oxygen toxicity
- improves oxygen diving procedures described in the US Navy Diving Manual
- includes procedures applicable to undertaking nitrox dives in combination with oxygen dives
- pitches the material at highest technology readiness levels, i.e. 9 TRL
- aims to increase tactical capabilities of conducting diving special operations

This book is aimed at researchers, professionals and graduate students in life support system design, diving submarine safety, ventilation, health, sanitary engineering, mining engineering and working environment in chambers or closed compartments.

Diving Sciences

Series Editor: Ryszard Kłos

The series is aimed at encouraging scientists from around the world to publish research related to diving and hyperbaric exposures pertaining to the last Technology Readiness Levels (8 TRL-9 TRL), with a particular focus on system prototype demonstration in an operational environment, system complete and qualified, and actual system proven in operational environment. The intended audience includes researchers in diving science, military and civilian divers, diving contractors, navies, defense and civilian diving schools and related academic audiences.

Oxygen Diving
Ryszard Kłos

For more information about this series, please visit: https://www.routledge.com/Diving-Sciences/book-series/CRCDS

Oxygen Diving

Ryszard Kłos

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

First edition published 2023
by CRC Press
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742

and by CRC Press
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

CRC Press is an imprint of Taylor & Francis Group, LLC

ISBN: 978-1-032-31389-4 (hbk)
ISBN: 978-1-032-31390-0 (pbk)
ISBN: 978-1-003-30950-5 (ebk)

DOI: 10.1201/9781003309505

Typeset in Times
by Apex CoVantage, LLC

In appreciation of her assistance and perseverance, I dedicate this book to my dear wife Yvonne, who through the years has supported and aided me in my efforts.

Contents

About the Author

Ryszard Kłos graduated from the Technical University of Wrocław with an MSc in physicochemistry. He started his professional carrier in the Institute of Low Temperature and Structural Research, Polish Academy of Sciences, Wrocław.

In 1985 he attended military training required of university graduates and graduated from Chemical Warfare College. Next year he joined the Polish Navy as platoon leader in Military Diving School. In 1988 he was transferred to the Naval Academy to the Department of Diving Gear and Underwater Work Technology where he earned his PhD in the field of design and operation of machines. He completed a post-doctoral fellowship at the DR-DC Toronto (former: Defence and Civil Institute of Environmental Medicine). He defended his habilitation thesis (higher PhD thesis) in the field of machine operation at Gdańsk University of Technology.

The author is a retired Polish Navy captain. He is currently employed as Associate Professor at the Polish Naval Academy, where he is responsible for various diving and physicochemical research projects and programs. He has written nine books and many scientific articles. From 2012 to 2015 he served as Deputy of Rector for Scientific Research at the Polish Naval Academy. From 2004 to 2007 he was President of the Polish Hyperbaric Medical and Technical Society.

Preface

The book is one of the publications in the series Diving Sciences aimed at publishing research on diving and hyperbaric exposures pertaining to technology readiness levels (TRL). It is especially focused on a system prototype demonstration in an operational environment, a system complete and qualified, and a system proven in an operational environment. The intended audience includes researchers in diving science, military and civilian divers, and diving contractors, navies, defense and civilian diving schools and related academic audiences.

This book will be of use to diving scientists, as they must assess the risk of central nervous syndrome, and it will also be useful for special operations forces tactics specialists, because:

- navies expect progress in technologies of diving dedicated to use in military operations
- defense diving schools expect materials for training in modernized technologies of diving
- military divers expect aided materials in the process of self-education

Civilian diving with oxygen is illegal in many countries, and its use is only possible during the decompression phase, where the risk of oxygen toxicity is minimal. The models described in the book allow assessing the risk of oxygen toxicity, which may be useful for technical divers.

The book deals with the validation process of a real system proven in an operational environment and is not intended as a summary or scientific discussion of current trends in biochemical advances in oxygen toxicity research. The book explains only the necessary biological mechanisms needed to understand the content, bearing in mind that it will be read by users who do not need specialist knowledge of biology, chemistry, biochemistry, biophysics, toxicology and so on, and focuses only on oxygen toxicity models that have been proven beyond any doubt with an assumed accuracy limit needed in practical use. This validation process is described in detail in the book as its aim/canvas.

Validation studies are time-consuming and require a high budget. If someone would like to save a lot of time and money, it is much better to first evaluate the scientific process carried out in Poland and then implement their own research.

The described model of central nervous syndrome caused by oxygen toxicity is based on survival analysis. It was based on earlier experiments performed by Great Britain during World War II and introduced by the United States in the 1970s. This theory is still valid and is used by most navies.

During the research conducted in Poland the model was validated, which is described in the book. Additionally, this technology was further developed and now embraces not only the oxygen technology but the oxygen/nitrox one as well.

The approach is similar to finding a new drug therapy. The studies described in the book relate to clinical trials that were organized similarly to the clinical trials of

new drug therapies with the approval of the Bioethics Committee in accordance with the Declaration of Helsinki. The research involved not the use of a new drug but the optimization of the procedure for its use. That means the research described in the book was formally carried out as the implementation of a new treatment procedure using a classic drug, which consisted of checking the optimal method of its dosing. Therefore, the book does not provide a critical analysis of current medical reports on the mechanism of the toxic effect of oxygen as its content relates to the possibility of practical optimal application of the achievements to date in this field.

An example of the equipment described in the book is a French-made diving apparatus, but all special operations forces can use the technology modified in Poland, especially if they use alternatively supplied diving apparatuses, such as

- *oxy – CCR/Nx – SCR AMPHORA SCUBA*[1]
- *oxy – CCR/Nx – SCR LAR VII Combi FA (LEBA* 24*/LAR* 5010*) SCUBA*
- *oxy – CCR/Nx – SCR Oxy – Mix SCUBA* and similar construction

but other countries can use this technology to a limited extent.

From the date of its establishment (1976), evaluation and study of diving equipment and decompression systems has been the primary task carried out by the Department of Underwater Work Technology[2] of the Naval Academy. The projects referred to required proper research stations. We mostly built them ourselves or acquired them special through orders. At the very beginning, the special purpose team of technicians was established for this task. They were able to produce technology demonstrators[3] as well as prototypes of diving and scientific instruments. Experimental Deepwater Diving Complex DGKN-120 was supposed to be a universal test bench and was designed to provide comprehensive research capabilities for the diving apparatus. At that time, the initial concepts of research stations were designed by the first head, late Cpt(N) Medard Przylipiak MSc Eng. The ideas of conducting a comprehensive study of diving apparatus were common with his successors: the late Cmdr. Marian Pleszewski MSc Eng. and Cpt(N) Stanislaw Skrzyński PhD Eng., which did not prevent them from making other scientific achievements.[4] One person who played a leading role was Cpt(N) Prof. Tadeusz Doboszyński PhD, DSc Med. from the Military Medical Academy.

It was Cpt(N) Stanislaw Skrzyński MSc Eng. who became an inspiring leader in the development and research on new types of diving equipment. The results of this work have been largely wasted due to the failure to promote research focused on developing the original Polish diving apparatus and decompression systems.

Bearing in mind the old concepts and the undeniable achievements, efforts were made to raise funds to continue the work done by their predecessors. Initially, the purchases of foreign diving equipment facilitated this task, at the same time creating a need to start the implementation work.[5] The effective stage of research was reached with modelling breathing in *CCR* and *SCR* systems, which made it possible to connect the diving apparatus model with the model of decompression diving. Another completed project made it possible to develop a statistical approach to the safety of diving. The research into saturation diving and decompression systems allowed us to extend our laboratory facilities and expand the filed specific knowledge. Using

predecessors' ideas and not-so-small funds, we managed to build a material base and theoretical knowledge to carry out research on diving apparatuses and decompression systems. The research facilities are also used for training and as an emergency center. It is hoped that these efforts will not be wasted and Poland will return to and continue to be present among the countries developing diving technologies.

NOTES

1 *CCR* – closed circuit rebreather; *SCR* – semiclosed circuit rebreather; *Nx* – nitrox; *SCUBA* – self-contained breathing apparatus.
2 Formerly the Department of Diving Gear and Underwater Work Technology.
3 By technology demonstrator it is meant the practical demonstration of technical solutions aimed at the development of a particular system, demonstrating the possibility of achieving the required parameters for this system.
4 For example, the implementation of saturation dives.
5 But giving only evidence of the possibility of using domestic supplies.

Acknowledgments

Apart from financing, the presented research required access to unique combat equipment. I express my gratitude to the Navy Command of the Republic of Poland and the 3rd Ship Flotilla for the trust that I received.

The research included experiments on humans, which required consent of the Scientific Research Ethics Committee. In addition to appreciation to the predecessors, gratitude must be expressed for the contribution given by the research staff of the department and cooperating medical doctors from the Military Medical Institute. Of them Cmdr. Maciej Konarski PhD Med. has significantly contributed to assembling the experimental data described in this monograph.

Thanks for the confidence demonstrated by the divers and professionals from military units, police, anti-terrorist groups and others who have supported this work. Also, because of the considerable investment by the Ministry of Defense, Ministry of Science and Higher Education, and National Research and Development in the research carried out in the department, the desired and expected results have been attained.

In particular, I would like to express my gratitude to Karina Kowalska MSc, Prof. Grzegorz Kowalski PhD and Kazimierz Szczepański PhD, who reviewed the entire manuscript.

Definitions

Item	Description
Bathynautics	is the totality of knowledge about human underwater activities.
Bradycardia	is herein defined as the state when the heart rate decreases upon exposure of the body to hyperbaric conditions compared to the heart in normobaric conditions.
Buffer	is a solution whose *pH* value after the addition of small amounts of strong acids or alkali as well as after dilution with water is relatively constant.
Catalysts	are substances that increase the rate of reaction but remain unchanged after the reaction.
Catalytic reaction	(catalysis) is a chemical reaction in which a change in reaction rate occurs under the influence of a catalyst
Chemical equation	(reaction equation) is a quick record of the chemical reaction; the starting materials (substrates) are located on the left side of the formula and the substances obtained in the reaction (reaction products) are on the right side.
Chemical reaction yield	(efficiency of a chemical reaction) is the ratio of the amount of reacted material to the amount of matter that could theoretically react by chemical reaction.
Cycle ergometer	is a device with a structure similar to a bicycle, controlled by inhibiting the pedal effort at a controlled rate of the cycling.
Cytochromes	proteins present in the cell mitochondria with biocatalyst function involved in electron transport.
Decompression	with respect to the dive is a gradual lowering of pressure applied to the diver at the exit of the hyperbaric environment carried out so that there are no signs of disease.
Diffusion	is the spontaneous mixing of the components of the system as a result of the chaotic motion of particles.
Dissimulation	is understood here as a presence manifested in an attempt to meet the norms or hide the actual situation and feelings, impulses, behaviors, etc.
Endothermic reaction	is chemical reaction that occurs with the heat being absorbed.
Enzyme	is mostly protein and macromolecular chemical compound regulating life processes.
Equilibrium constant[1]	is the number given by the ratio of the product of the molar concentrations of the products to the product of the molar concentration of substrates – the molar concentrations should be expressed in molar fractions and raised to the power such as results from the reaction stoichiometric ratio
Exothermic reaction	is a chemical reaction that proceeds with the liberation of heat.
Homeostasis	is the ability of a living organism, by proper coordination and regulation of life processes, to maintain a relatively constant state of equilibrium, for example, blood composition, temperature, etc.
Hyperbaric oxygen therapy	is a therapeutic procedure often used for general and local tissue oxygenation against anaerobes, after gas poisoning, to secure the graft, frostbite, burns, radioactive damage, osteomyelitis, slow-healing wounds, sudden deafness, etc.
Hypercapnia	is a state of elevated partial pressure of the CO_2 in the blood above $pCO_2 > 45$ *mmHg*, referred here as the symptoms of CO_2 poisoning.
Hyperoxia	is a state of breathing respiratory medium, wherein the oxygen partial pressure exceeds 21 *kPa*, this term is used herein to cases of breathing with medium with the partial pressure of oxygen, which creates a toxic threat.

Item	Description
Hypocapnia	(also hypocarbia) is a state of reduced partial pressure of CO_2 in the blood below normal values.
Hypoxemia	is a reduction of the diffusion of the oxygen in the lungs.
Hypoxia	is the state of oxygen deficiency in the tissue resulting from reduced oxygen diffusion in the lungs (hypoxemia) or disorder of the blood oxygen transport to the tissues (ischemia).
Ischemia	is a disorder of oxygen transport by blood to the tissues.
Mathematical model	is a mathematical description of the behavior of the modelled system, usually expressed in the form of algebraic mathematical equations.
Metabolite	is an organic or inorganic metabolic product.
Mitochondria	is a structure surrounded by a membrane, present in the plasma of most nucleated cells, and is the place where in the process of cellular respiration most energy-carrying compounds are produced.
Model	is a system whose function is to imitate the distinguished features of another system, known as the original.
Mol	is a basic unit in the SI system that specifies the amount of substance in the system.[2]
Paresthesia	is a deficit in sensorial perception involving the wrong location of the stimulus and warped fillings described as tingling, numbness, etc.
Premix	is a mixture of two or more components standardized prior to use.[3]
Preoxygenation	is flushing the body with oxygen.[4]
Radical	is a group of atoms, generally incapable of independent existence, having unpaired electrons.[5]
Reaction kinetics	is reaction duration/mechanism as a function of time.
Reaction mechanism	describes a mechanism created during the chemical reaction via intermediate stages, which further result in final products, as summarized in reaction equation, illustrating transition from the starting particles into particles which are reaction products.
Respiratory dead space volume	is the lung space volume in which the ventilation does not occur or mass transfer occurs only to a limited extent.
Saturated solution	is a solution which, under specified conditions, is/can be in equilibrium with excess of the solute.
Semi-empirical methods	are methods describing the behavior of the object according to criterion equation[6] typically containing one or several constants determined empirically for a model, but these do not have constant physical interpretation and are often dependent on the units of measurement.[7]
Solution concentration	is the amount of solute in a given amount of solvent; concentration of the solution most often is expressed using a fraction or percentage concentration.[8]
Somatic	concerns the body; carnal, physical.
System	is distinguished from the reality collection of elements with links between them (Other elements are outside the system and form the system context. Links between system elements and context elements create interactions between the system and the environment).
Target strength	Strength is the most commonly expressed in decibels [$dB@1\ m$] as the ratio of the intensity of the wave [$W \cdot m^{-2}$] reflected from the target toward the receiver at a distance from its center and a intensity of the acoustic wave [$W \cdot m^{-2}$] incident on the object from the receiver.

NOTES

1 If the reaction reaches equilibrium it can be characterized by the equilibrium constant, which depends only on the type of reaction and temperature.
2 1 mole of the substance occurs when the number of particles is equal to the number of atoms contained in the carbon isotope ^{12}C with mass 0.012 *kg*.
3 This term is used here to emphasize that nitrox used in a diving apparatus must be premixed, seasoned, tested, certified and operationally tested before use.
4 In normal tissues dissolved nitrogen is in equilibrium with atmospheric air, but during the initial phase of diving nitrogen is purged from the tissues, causing delay in the dissolution of nitrogen in the tissues during the phase of nitrox diving, thus allowing a slight shortening of the decompression process without increasing the risk of decompression sickness (*DCS*).
5 Free valences.
6 Received, e.g. via dimensional analysis.
7 Algebraic model thus obtained is not adequate when you change the units of measurement, and due to the approximate nature of the relationship (consisting of approximately a function of the unknown laws of physics) semi-empirical and empirical models are valid only to the extent of their determination and allow in this field interpolation and every extrapolation is always risky.
8 There are several kinds of concentration expressed using a fraction or percentage concentration: mole (normal), mass, volume, etc.

Acronyms

Item	Description
CCR SCUBA	closed circuit rebreather self-contained breathing apparatus
CNSyn	oxygen toxicity impact on the central nervous system is called the Paul Bert effect; sometimes the acronym *CNS* for central nervous syndrome is used, but for the purposes of this book, in order to distinguish it from the acronym used to define the central nervous system (*CNS*), *CNSyn* will be used
CO_2	carbon dioxide
fsw	feet sea water
GABA	There are two *GABA* types of receptors binding γ-amino butyric acid: – $GABA_A$ adrenoceptor regulates the influx of chloride ions into the cell hindering the formation of action potentials responsible for providing information in the nervous system – $GABA_B$ adrenoceptor regulates the flow of potassium ions and calcium to neutralize the effect of chloride ions and regulates the release of neurotransmitters
HBO	hyperbaric medicine (*HBOT* – hyperbaric oxygen therapy) is the use of pressurized oxygen for medical purposes; in addition to the treatment of a decompression sickness pressure it is a good method for the treatment of gangrene, diabetic foot, exhaust gases and carbon monoxide poisoning and helps in the healing of wounds after frostbite and skin transplantation; there are also reports of its use in regenerating nerve tissue, especially the auditory nerve
IR	infrared
MoD	Ministry of Defense
OTT	oxygen tolerance test
pH	the exponent of multiplicity of hydrogen ions,[1] which is regarded as a physical quantity and a quantitative measure of the activity of hydrogen ions in solution
ppm	parts per million
SCR SCUBA	semiclosed circuit rebreather self-contained breathing apparatus
SEV	surface equivalent value
STANAG	NATO standardization agreement
STP	standard temperature and pressure – $T = 273\ K$ and $p = 101{,}325\ kPa$
TT	treatment table

NOTE

1 Negative logarithm of the hydrogen ion activity; pH of water and neutral solution $pH = 7.0$, acidic solutions $pH < 7$, alkaline $pH > 7$.

Introduction

This monograph contains the results of studies conducted within the framework of development project Nº OR00000108 entitled "Designing Decompression in Combat Missions" and the development project Nº OR00009811 entitled "Detection and Prevention of Diver Terrorist Threats." Both projects were financed by the Polish National Research Council. The monograph contains the results of the research on the possibilities of conducting nitrox[1] (*Nx*)/oxygen exposure using a diving apparatus type *oxy – CCR/Nx – SCR AMPHORA SCUBA*. It also contains references to the other published results dedicated to the design and the methods of testing semiclosed and closed circuit diving apparatuses. The reason for undertaking the research was the need to adapt the diving technology to the tasks planned for the future.

FRAMEWORK

Research and training was carried out under the authorization obtained from the Bioethics Committee of the Military Medical Institute. From the start, it was assumed that the technical capabilities of the apparatus should contribute to improving the flexibility of combat missions. The *oxy – CCR/Nx – SCR AMPHORA SCUBA* apparatus has been designed to facilitate deployment of assault groups/special forces through the torpedo hatch of large submarines staying at periscope depth. The launch of an underwater mission at depths below 6 mH_2O with the use of oxygen apparatus type *oxy – CCR SCUBA* significantly limits the duration time and the depth of the mission, which makes it less effective. On the other hand, resignation from the benefit of a hidden transfer and from the possibility to launch a mission of a special group/special section from the submarine is, from a tactical point of view, unreasonable exclusion. It was recognized that the best option would be to start the mission using *Nx* and semiclosed circuit *Nx – SCR SCUBA* then proceed to a transit depth $H \leq 6\ mH_2O$ and finally continue the mission using oxygen in a closed circuit *oxy – CCR SCUBA*. In general, the depth of the *Nx*[2] diving phase does not exceed 24 mH_2O[3] – see Figure 0.1.

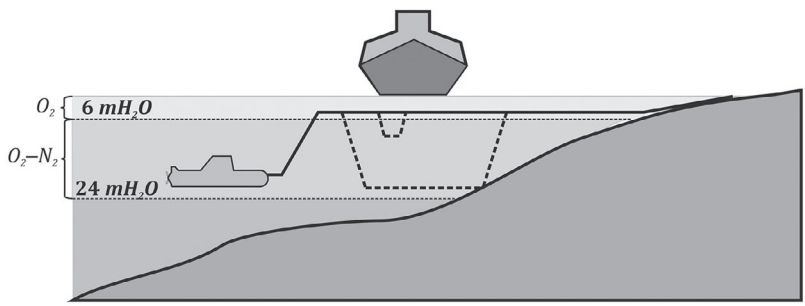

FIGURE 0.1 Typical dive profile for oxy/Nx dives

DOI: 10.1201/9781003309505-1

SUMMARY

The research program focused on two areas. The first was to introduce a method of transit-type dives using oxygen with the possibility of one trip below the depth of transit. The possibility of making a second trip of this kind, which would complete the dive, was also investigated. During this phase of research, the closed circuit mode of the *CCR* oxygen apparatus was used: *oxy – CCR AMPHORA SCUBA*.

In addition to evaluating the risks of oxygen toxicity that could occur during trips to a depth greater than the maximum depth of the transit, research was also focused on developing rules of purging the respiratory loop of the apparatus.

The second area covered the use of *oxy – CCR/Nx – SCR AMPHORA SCUBA* apparatus in *Nx* mode and was focused on developing tables and know-how for an *Nx* trip after the initial phase of transit. Throughout this initial phase, the apparatus is used in oxygen closed circuit mode: *oxy – CCR AMPHORA SCUBA*. During a dive to a depth greater than the maximum depth of the transit, the apparatus is switched to *Nx* supply in semiclosed circuit mode: *Nx – SCC AMPHORA SCUBA*. The main task of the research was to establish the maximum dive time while using *Nx*, assuming direct decompression obligation after reaching the specified maximum depth of the trip. While determining the maximum dive time, the influence of the initial preoxygenation[4] had to be taken into consideration.

NOTES

1 A nitrogen-oxygen gas mixture in which the oxygen content is different from that in the air.
2 Prior to the underwater mission which uses oxygen as a breathing medium.
3 For *Nx – SCR AMPHORA SCUBA* apparatus, *Nx* maximum operational depth can be deeper (see Chapter 1).
4 Flushing the body with oxygen. In standard conditions, nitrogen dissolved in tissues is in equilibrium with atmospheric air, but during the initial phase of oxygen diving it is flushed out from the tissues, causing delay in the dissolution of nitrogen in the tissues during the nitrox phase of diving, which allows a slight shortening of the process of decompression without the increased risk of decompression sickness.

Subject of the Research

AQUA LUNG . 2004. AMPHORA Oxygen and Mix Gas Diving Equipment – Operating and Maintenance Manual. Nice: La Spirotechnique I.C. AMPHORA Réf. A658.

Brennan DMA & Bdonchuk WW . 1975. Oxygen consumption of SCUBA divers – a technique for measurement and analysis. In Proceedings of the 6-th International Conference on Underwater Education. San Diego: National Association of Underwater Instructors.

Haux G . 1982. Subsea Manned Engineering. London: Bailliére Tindall. ISBN 0-7020-0749-8.

Kłos R . 2000. Aparaty Nurkowe z regeneracją czynnika oddechowego. Poznań: COOPgraf. ISBN 83-909187-2-2.

Kłos R . 2012. Możliwości doboru ekspozycji tlenowo-nitroksowych dla aparatu nurkowego typu AMPHORA. Gdynia: Polskie Towarzystwo Medycyny i Techniki Hiperbarycznej. ISBN 978-83-924989-8-8.

Kłos R. 2021. Ventilation of Normobaric and Hyperbaric Objects. Boca Raton, FL: CRC Press (Taylor & Francis Group, LLC). ISBN: 978-0-367-67523-3 (hbk) ISBN: 978-0-367-67524-0 (pbk) ISBN: 978-1-003-13164-9 (ebk).

Przylipiak M & Torbus J . 1981. Sprzęt i prace nurkowe-poradnik. Warszawa: Wydawnictwo Ministerstwa Obrony Narodowej. ISBN 83-11-06590-X.

Williams S . 1975. Engineering principles of underwater breathing apparatus. In The Physiology and Medicine of Diving, ed. PB Bennett & DH Elliott , 34–46. London: Baillière Tindall.

Inherent Unsaturation

Åstrand P-O & Rodahl K. 1977. Textbook of Work Physiology: Physiological Bases of Exercises. New York: McGraw-Hill, Inc. ISBN 0-07-002406-5.

Behnke AR . 1967. The isobaric (oxygen window) principle of decompression. In The New Thrust Seaward. Transactions of the Third Annual Conference of the Marine Technology Society Conference, San Diego. 5–7 June. Washington, DC: Marine Technology Society.

Berg JM , Tymoczko JL & Stryer L. 2013. Biochemistry. New York: W.H. Freeman and Company. ISBN: 1-4292-8360-2. ISBN-13: 978-1-4292-8360-1.

Cole B. 1993. Decompression and Computer Assisted Diving. Biggin Hill: Dive Information Company. ISBN 0-9520934-0-5.

Corda M , De Rosa MC , Pellegrini MG , Sanna MT , Olianas A , Fais A , Manca L , Masala B , Zappacosta B , Ficarra S , Castagnola M & Giardina B . 2000. Adult and fetal hemoglobin J-Sardegna [α50(CE8)His→Asp]: functional and molecular modelling studies. Biochem. J., 346, 193–199.

Ekeloef NP , Eriksen J & Kancir CB . 2001. Evaluation of two methods to calculate p50 from a single blood sample. Acta. Anaesthesiol. Scand., 45, 550–552. http://doi.org/10.1034/j.1399-6576.2001.045005550.x.

Kenny JE . 1973. Business of Diving. Houston: Gulf Publishing Co. ISBN 0-87201-183-6.

Kłos R. 2021. Ventilation of Normobaric and Hyperbaric Objects. Boca Raton, FL: CRC Press (Taylor & Francis Group, LLC). ISBN: 978-0-367-67523-3 (hbk). ISBN: 978-0-367-67524-0 (pbk). ISBN: 978-1-003-13164-9 (ebk).

Kot J , Sicko Z & Doboszynski T. 2015. The extended oxygen window concept for programming saturation decompressions using air and Nitrox. PLoS ONE, 6, 1–20. http://doi.org/10.1371/journal.pone.0130835.

Kwasiborski PJ , Kowalczyk P , Zieliński J , Przybylski J & Cwetsch A . 2010. Znaczenie powinowactwa hemoglobiny do tlenu w adaptacji do hipoksemii. Polski Merkuriusz Lekarski., 28, 166–260.

Lamberdsen CJ , Kough RH , Cooper DY , Emmel GL , Loeschcke HH & Schmidt CF . 1953. Oxygen toxicity. Effects in man of oxygen inhalation at 1 and 3,5 atmospheres upon blood gas transport, cerebral circulation and cerebral metabolism. J. Appl. Physiol., 9, 471–486.

Lobdell DD . 1981. An invertible simple equation for computation of blood O2 dissociation relations. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol., 50, 971–973.

Nunn JF . 1993. Nunn’s Applied Respiratory Physiology. Jordan Hill: Butterworth-Heinemann Ltd. ISBN 0 7506 1336 X.

Przylipiak M & Torbus J. 1981. Sprzęt i prace nurkowe-poradnik. Warszawa: Wydawnictwo Ministerstwa Obrony Narodowej. ISBN 83-11-06590-X.
Stryer L. 1997. Biochemia. Warszawa: Wydawnictwo Naukowe PWN. ISBN 83-01-12044-4.
Tikuisis P & Gerth WA . 2003. Decompression theory. In Bennett and Elliott's Physiology and Medicine of Diving, ed. AO Brubakk & TS Neuman , 419–494. Edinburgh: Saunders.
Van Liew HD , Bishop B , Walder PD & Rahn H . 1965. Effects of compression on composition and absorption of tissue gas pockets. J. Appl. Physiol., 20, 927–933.
Vann RD . 1989. The physiology of NITROX diving. In Workshop on Enriched Air NITROX Diving, ed. RW Hamilton , DJ Crosson & AW Hulbert , 85–104. Rockville: National Oceanic and Atmospheric Administration.
West JB & Luks AM . 2016. West's Respiratory Physiology – The Essentials. Philadelphia: Wolters Kluwer. ISBN 978-1-4963-1011-8.

Oxygen Toxicity

Anderson B , Saltzman HA & Barbee JY . 1965. Retinal vascular and functional response to hyperbaric oxygenation. In Proceedings of the Third International Conference on Hyperbaric Medicine, ed. IW Brown & BG Cox , 276–280. Durham: Duke University.
Arieli R , Yalov A & Goldenshluger A . 2002. Modeling pulmonary and CNS O2 toxicity and estimation of parameters for humans. J. Appl. Physiol., 92, 248–256.
Arieli R . 2019. Calculated risk of pulmonary and central nervous system oxygen toxicity: Toxicity index derived from the power equation. Diving Hyperb. Med., 49, 154–160. http://doi.org/10.28920/dbш49.3.
Bader N , Bosy-Westphal A , Koch A , Rimbach G , Weimann A , Poulsen HE & Müller MJ . 2007. Effect of hyperbaric oxygen and vitamin C and E supplementation on biomarkers of oxidative stress in healthy men. Br. J. Nutr., 98, 826–833.
Bartosz G . 2008. Druga twarz tlenu – wolne rodniki w przyrodzie. Warszawa: Wydawnictwo Naukowe PWN. ISBN 978-83-01-13847-9.
Bennett PB & Elliott DH . 1993. The Physiology and Medicine of Diving. London: W.B. Saunders Company Ltd. ISBN 0-7020-0538-X.
Berg JM , Tymoczko JL & Stryer L . 2013. Biochemistry. New York: W.H. Freeman and Company. ISBN: 1-4292-8360-2. ISBN-13: 978-1-4292-8360-1.
Betts EA . 1992. The Application of Enriched Air Mixtures. New York: American Nitrox Divers Inc.
Bitterman N . 2004. CNS oxygen toxicity. Undersea Hyperb. Med. J., 31, 63–72.
Brubakk AO & Neuman TS . 2003. Bennett and Elliott's Physiology and Medicine of Diving. London: Saunders. ISBN 0-7020-2571-2.
Butler FK & Knafelc ME . 1986. Screening for oxygen intolerance in U.S. Navy divers. Undersea Biomed. Res., 13, 91–98.
Butler FK & Thalmann ED . 1986a. Central Nervous System oxygen toxicity in closed-circuit SCUBA divers II. Undersea Biomed. Res., 13, 193–223.
Butler FK & Thalmann ED . 1986b. CNS Oxygen Toxicity in Closed-Circuit SCUBA Divers III. Panama City: USN Experimental Diving Unit. Report No 5-86.
Butler FK & Thalmann ED . 1984. CNS oxygen toxicity in closed-circuit SCUBA diving. In Proceedings of the Eight Symposium Underwater Physiology, ed. AJ Bachrach & MM Matzen , 15–30. Bethesda: Undersea Madical Society.
Clark JM & Thom SR . 2003. Oxygen under pressure. In Bennett and Elliott's Physiology and Medicine of Diving, ed. AO Brubakk & TS Neuman , 358–418. Edinburgh: Saunders.
Comex . 1986. Medical Book. Marseille: Comex.
Donald KW . 1992. Oxygen and the Diver. Harley Swan: The SPA Ltd. ISBN 1-85421-176-5.
Donald KW . 1955. Oxygen bends. J. Appl. Physiol., 7, 639–644.
Donald KW . 1947. Oxygen poisoning in man part I. Br. Med. J., 7, 667–672.
Farmer JC & Thomas WG . 1976. Ear and sinus problems in diving. In Diving Medicine, ed. RH Strauss . New York: Grune & Stratton, Inc.

Fire Research, Test, Development and Education Centre . 1993. Test Report: Safety at 8% Oxygen – 15 Minutes. Copenhagen: Fire research, Test, Development and Education Centre.
Groöger M , Öter S , Simkova V , Bolten M , Koch A , Warninghoff V , Georgieff M , Muth CM , Speit G & Radermacher P . 2009. DNA damage after long-term repetitive hyperbaric oxygen exposure. J. Appl. Physiol., 106, 311–315.
Hamilton RW . 1989. Tolerating exposure to high oxygen levels: Repex and other methods. Mar. Tech. Soc. J., 23, 19–25.
Hamilton RW , Kenyon DJ & Peterson RE . 1988. REPEX Habitat Diving Procedures: Repetitive Vertical Excursions, Oxygen Limits, and Surfacing Techniques. Washington, DC: National Oceanic and Atmospheric Administration. Technical Report 88-1B.
Hamilton RW , Kenyon DJ , Peyerson RE , Butler GJ & Beers DM . 1988. REPEX: Development of Repetitive Excursions, Surfacing Techniques, and Oxygen Procedures for Habitat Diving. Washington, DC: National Oceanic and Atmospheric Administration. Technical Report 88-1A.
Harabin AI & Survanshi SS . 1993. A Statistical Analysis of Recent NEDU Single-Depth Human Exposures to 100% Oxygen at Pressure. Bethesda: Naval Medical Research Institute. NMRI 93-59; AD-A237 488.
Harabin AL , Homer LD , Weathersby PK & Flynn ET . 1987. An analysis of decrements in vital capacity as an index of pulmonary oxygen toxicity. J. Appl. Physiol., 63, 1130–1135.
Harabin AL , Survanshi SS & Homer LD . 1994. A Model for Predicting Central Nervous System Toxicity from Hyperbaric Oxygen Exposure in Man: Effects of Immersion, Exercise, and Old and New Data. Bethesda: Naval Medical Research Institute. NMRI 94-0003; AD-A278 348.
Harabin AL , Survanshi SS & Homer LD . 1995. A model for predicting central nervous system toxicity from hyperbaric oxygen exposure in humans. Toxicol. Appl. Pharmacol., 132, 19–26.
Kenny JE . 1973. Business of Diving. Houston: Gulf Publishing Co. ISBN 0-87201-183-6.
Kłos R . 2000. Aparaty Nurkowe z regeneracją czynnika oddechowego. Poznań: COOPgraf. ISBN 83-909187-2-2.
Lamberdsen CJ , Kough RH , Cooper DY , Emmel GL , Loeschcke HH & Schmidt CF . 1953. Oxygen toxicity. Effects in man of oxygen inhalation at 1 and 3,5 atmospheres upon blood gas transport, cerebral circulation and cerebral metabolism. J. Appl. Physiol., 9, 471–486.
NOAA . 2001. NOAA Diving Manual – Diving for Science and Technology. Flagstaff: Best Publishing Co. ISBN 0-941332-70-5.
NOAA . 2017. NOAA Diving Manual – Diving for Science and Technology. Flagstaff: Best Publishing Co. ISBN 9781930536883.
Nowotny F & Samotus B . 1971. Biochemia ogólna. Warszawa: PWRiL.
NSO . 2020. Allied Guide to Diving Medical Disorders. Brussels: NATO Standardization Office (NSO). ADivP-02 (STANAG 1432).
Przylipiak M & Torbus J . 1981. Sprzęt i prace nurkowe-poradnik. Warszawa: Wydawnictwo Ministerstwa Obrony Narodowej. ISBN 83-11-06590-X.
Rencricca NJ & Coleman RM . 1979. Modulation of Oxygen Toxicity by Select Anti-Melanogenic Compounds. Lowell: University of Lowell. ADA078239.
Rutkowski D . 1990. Nitrox Manual. Key Largo: Hyperbarics International, Inc.
Shilling CW . 1981. A History of the Development of Decompression Tables. Bethesda: Undersea Medical Society, Inc.
Shykoff B . 2007. Performance of Various Models in Predicting Vital Capacity Changes Caused by Breathing High Oxygen Partial Pressures. Panama City: Navy Experimental Diving Unit. NEDU Report TR 07-13.
Strauss RH . 1976. Diving Medicine. New York: Grune & Stratton Inc. ISBN 0-8089-0699-2.
Stryer L . 1997. Biochemia. Warszawa: Wydawnictwo Naukowe PWN. ISBN 83-01-12044-4.
Swiergosz MJ , Keyser DO & Koller WA . 2004. Melatonin Does Not Provide Protection Against Hyperbaric Oxygen (HBO) Induced Seizures. Silver Spring: Naval Medical Research Institute. NMRC 2004-001.
Szefostwo Ratownictwa Morskiego . 2007. Tymczasowa instrukcja: Standardowy test ciśnieniowy i tolerancji tlenowej. Gdynia: Dowództwo Marynarki Wojennej. Załącznik 2 do rozkazu Dowódcy Marynarki Wojennej nr 30/SRM z dn. 02.04.2007.
Torbati D , Church DF , Keller JM & Pryor WA . 1992. Free radical generation in the brain precedes hyperbaric oxygen induced convulsions. Free Radic. Biol. Med., 13, 101–106.
US Navy Diving Manual . 1980. Carson: Best Publishing Co. NAVSEA 0994-LP-001-9010.

US Navy Diving Manual . 2008. Washington, DC: The Direction of Commander Naval Sea Systems Command. 0910-LP-106-0957.
US Navy Diving Manual . 2016. Washington, DC: The Direction of Commander Naval Sea Systems Command. SS521-AG-PRO-010 0910-LP-115-1921.
Vann RD . 1989. The physiology of NITROX diving. In Workshop on Enriched Air NITROX Diving, ed. RW Hamilton , DJ Crosson & AW Hulbert . Washington, DC: National Oceanic and Atmospheric Administration.
Vann RD . 1993. Oxygen exposure management. AquaCorps., 7, 54–59.
Walters KC , Gould MT , Bachrach EA & Butler FK . 2000. Screening for oxygen sensitivity in US Navy combat swimmers. Undersea Hyper. Med., 27, 21–26.

Basics of Survival Analysis

Brubakk AO & Neuman TS . 2003. Bennett and Elliott's Physiology and Medicine of Diving. London: Saunders. ISBN 0-7020-2571-2.
Donald KW . 1992. Oxygen and the Diver. Harley Swan: The SPA Ltd. ISBN 1-85421-176-5.
Evans M , Hastings N & Peacock B . 1993. Statistical Distributions. New York: John Willey & Sons, Inc. ISBN 0-471-55951-2.
Gerth WA . 2002. Overview of survival functions and methodoology. In Survival Analysis and Maximum Likelihood Techniques as Applied to Physiological Modeling, ed. PK Weathersby & WA Gerth , 1–28. Kensington: Undersea and Hyperbaric Medical Society Inc.
Harabin AL . 1993. Human Central Nervous System Oxygen Toxicity Data from 1945 to 1986. Bethesda: Naval Medical Research Institute. NMRI 93-03; AD-A268-225.
Harabin AL , Survanshi SS & Homer LD . 1994. A Model for Predicting Central Nervous System Toxicity from Hyperbaric Oxygen Exposure in Man: Effects of Immersion, Exercise, and Old and New Data. Bethesda: Naval Medical Research Institute. NMRI 94-0003; AD-A278 348.
Harabin AL , Survanshi SS & Homer LD . 1995. A model for predicting central nervous system toxicity from hyperbaric oxygen exposure in humans. Toxicol. Appl. Pharmacol., 132, 19–26.
Hills BA . 1997. Decompression Sickness – The Biophysical Basis of Prevention and Treatment: Vol. 1. Chichester: John Willey&Sons. ISBN 0-471-99457-X.
Kłos R . 2007. Zastosowanie metod statystycznych w technice nurkowej - Skrypt. Gdynia: Polskie Towarzystwo Medycyny i Techniki Hiperbarycznej. ISBN 978-83-924989-26.
Wienke BR . 2003. Basic Decompression Theory and Application. Flagstaff: Best Publishing Co. ISBN 1-930536-14-3.
Yarbrough OD , Welham W , Brinton ES & Behnke AR . 1947. Symptoms of Oxygen Poisoning and Limits of Tolerance at Rest and at Work. Washington: Naval Experimental Diving Unit. Research Report 01-47.

Oxygen Exposures

Butler FK & Thalmann ED . 1986a. Central Nervous System oxygen toxicity in closed-circuit SCUBA divers II. Undersea Biomedical Research, 13, 193–223.
Butler FK & Thalmann ED . 1986b. CNS Oxygen Toxicity in Closed-circuit SCUBA Divers III. Panama City: USN Experimental Diving Unit. Report No 5-86.
Butler FK & Thalmann ED . 1984. CNS oxygen toxicity in closed-circuit SCUBA diving. In Proceedings of the Eight Symposium Underwater Physiology, ed. AJ Bachrach & MM Matzen , 15–30. Bethesda: Undersea Madical Society.
Donald KW . 1992. Oxygen and the Diver. Harley Swan: The SPA Ltd. ISBN 1-85421-176-5.
Donald KW . 1955. Oxygen bends. J. Appl. Physiol., 7, 639–644.
Harabin AL , Survanshi SS & Homer LD . 1994. A Model for Predicting Central Nervous System Toxicity from Hyperbaric Oxygen Exposure in Man: Effects of Immersion, Exercise, and Old and New Data. Bethesda: Naval Medical Research Institute. NMRI 94-0003; AD-A278 348.

Harabin AL , Survanshi SS & Homer LD . 1995. A model for predicting central nervous system toxicity from hyperbaric oxygen exposure in humans. Toxicol. Appl. Pharmacol., 132, 19–26.
Pozański P . 2011. Współczesne zagrożenia elementów infrastruktury morskiej oraz systemy ich detekcji. Pol. Hyperb. Res., 35, 7–34.
US Navy Diving Manual . 2008. The Direction of Commander: Naval Sea Systems Command. 0910-LP-106-0957.
US Navy Diving Manual . 2016. Praca zbiorowa (revision 7). The Direction of Commander: Naval Sea Systems Command. SS521-AG-PRO-010 0910-LP-115-1921.

Oxygen/Nitrox Exposures

AQUA LUNG . 2004. AMPHORA Oxygen and Mix Gas Diving Equipment − Operating and Maintenance Manual. Nice: La Spirotechnique I.C. AMPHORA Réf. A658.
Bühlmann AA . 1984. Decompression-Decompression Sickness. Berlin: Springer-Verlag. ISBN 3-540-13308-9; ISBN 0-387-13308-9.
Bühlmann AA . 1995. Tauchmedizin. Berlin: Springer-Verlag. ISBN 3-540-58970-8.
Harabin AL , Survanshi SS & Homer LD . 1994. A Model for Predicting Central Nervous System Toxicity from Hyperbaric Oxygen Exposure in Man: Effects of Immersion, Exercise, and Old and New Data. Bethesda: Naval Medical Research Institute. NMRI 94-0003; AD-A278 348.
Kłos R . 2010. Detekcja śródnaczyniowej wolnej fazy gazowej. Pol. Hyperb. Res., 32, 15–30.
Kłos R . 2011a. Jednotkankowy model dekompresji ograniczonej procesem dyfuzji. Pol. Hyperb. Res., 35, 69−94.
Kłos R . 2011. Możliwości doboru dekompresji dla aparatu nurkowego typu CRABE – założenia do nurkowań standardowych i eksperymentalnych. Gdynia: Polskie Towarzystwo Medycyny i Techniki Hiperbarycznej. ISBN 978-83-924989-4-0.
Kłos R . 2007. Niektóre problemy związane z wyborem sposobu dekompresji. Pol. Hyperb. Res., 18, 33.
Walters KC , Gould MT , Bachrach EA & Butler FK . 2000. Screening for oxygen sensitivity in US Navy combat swimmers. Undersea Hyper. Med., 27, 21–26.

Experimental Diving

Harabin AL , Survanshi SS & Homer LD . 1994. A Model for Predicting Central Nervous System Toxicity from Hyperbaric Oxygen Exposure in Man: Effects of Immersion, Exercise, and Old and New Data. Bethesda: Naval Medical Research Institute. NMRI 94-0003; AD-A278 348.
Harabin AL , Survanshi SS & Homer LD . 1995. A model for predicting central nervous system toxicity from hyperbaric oxygen exposure in humans. Toxicol. Appl. Pharmacol., 132, 19–26.
Kłos R . 2010. Intravascular bubble detection. Pol. Hyperb. Res., 32, 15–30.
Kłos R . 2011. Możliwości doboru dekompresji dla aparatu nurkowego typu CRABE – założenia do nurkowań standardowych i eksperymentalnych. Gdynia: Polskie Towarzystwo Medycyny i Techniki Hiperbarycznej. ISBN 978-83-924989-4-0.
Kłos R . 2020. Ultrasonic detection of the intravascular free gas phase in research on diving. Pol. Marit. Res., 106, 176–186. ISSN 1233-2585, e-ISSN 2083-7429, DOI: 10.2478/pomr-2020-0039.
Nunn JF . 1993. Nunn’s Applied Respiratory Physiology. Jordan Hill: Butterworth-Heinemann Ltd. ISBN 0 7506 1336 X.
Troskalański AT . 1954. Hydromechanika techniczna-Hydraulika. Warszawa: Państwowe Wydawnictwo Techniczne.
US Navy Diving Manual . 2016. The Direction of Commander: Naval Sea Systems Command (revision 7). Washington. SS521-AG-PRO-010 0910-LP-115-1921.
Walters KC , Gould MT , Bachrach EA & Butler FK . 2000. Screening for oxygen sensitivity in US Navy combat swimmers. Undersea Hyper. Med., 27, 21–26.

Remarks

Behnke AR . 1967. The isobaric (oxygen window) principle of decompression. In The New Thrust Seaward. Transactions of the Third Annual Conference of the Marine Technology Society Conference, San Diego. 5–7 June. Washington, DC: Marine Technology Society.
Brubakk AO & Neuman TS . 2003. Bennett and Elliott's Physiology and Medicine of Diving. London: Saunders. ISBN 0-7020-2571-2.