



K. K. JAIN

Textbook of Hyperbaric Medicine

5th revised and
updated edition

Textbook of Hyperbaric Medicine

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HOGREFE



Library of Congress Cataloguing-in-Publication Data

is available via the Library of Congress Marc Database
under the LC Control Number 2008938004

National Library of Canada Cataloguing in Publication

Jain, K. K. (Kewal K.)

Textbook of hyperbaric medicine / K.K. Jain.—5th ed.

Includes bibliographical references and index.

ISBN 978-0-88937-361-7

1.Hyperbaric oxygenation. I.Title.

RM666.O83J35 2009 615.8'36 C2008-906643-X

Copyright © 2009 by Hogrefe & Huber Publishers

PUBLISHING OFFICES

USA: Hogrefe Publishing, 875 Massachusetts Avenue, 7th Floor Cambridge, MA 02139
Tel. (866) 823-4726, Fax (617) 354-6875, E-mail info@hogrefe.com

Europe: Hogrefe & Huber Publishers, Rohnsweg 25, 37085 Göttingen, Germany
Tel. +49 551 49609-0, Fax +49 551 49609-88, E-mail hh@hogrefe.com

SALES AND DISTRIBUTION

USA: Hogrefe Publishing, Customer Service Department, 30 Amberwood Parkway,
Ashland, OH 44805, Tel. (800) 228-3749, Fax (419) 281-6883, E-mail custserv@hogrefe.com

Europe: Hogrefe & Huber Publishers, Rohnsweg 25, 37085 Göttingen, Germany
Tel. +49 551 49609-0, Fax +49 551 49609-88, E-mail hh@hogrefe.com

OTHER OFFICES

Canada: Hogrefe & Huber Publishers, 1543 Bayview, Toronto, Ontario, M4G 3B5

Switzerland: Hogrefe & Huber Publishers, Länggass-Strasse 76, CH-3000 Bern 9

Hogrefe & Huber Publishers

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Printed and bound in Germany

ISBN 978-0-88937-361-7

To my wife Verena and my children Eric, Adrian, and Vivien Jain
for their patience during the preparation of this work

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Foreword

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Slowly but surely, hyperbaric medicine is becoming an established treatment modality for a variety of medical disorders, despite the rocky road that it has sometimes had to travel over the years. In some ways, I feel that the need for oxygen in medical treatments is akin to man's basic requirement for water and food, and I also think it is fair to say that the logic and utility of hyperbaric oxygen treatment now seem to be almost as undeniable as these basic requirements are.

It is certainly the case that, from time immemorial, remedies learned by trial and error have been handed down through the generations – with the result that many roots, berries, fruits, and leaves, as well as special waters containing minerals have been advocated throughout history for their curative powers. More recently, however, evidence-based medicine has come to the fore, demanding higher standards of evidence from basic and clinical/research trials and objective statistical results. One of the first instances of such objective studies in my lifetime was when Austin Bradford Hill and Richard Doll (Doll 2003) convinced colleagues to allocate patients with pulmonary tuberculosis randomly to prove the efficacy of streptomycin, although their trial followed a tradition started 200 years earlier by Linde, who provided citrus fruits aboard some, but not all ships in the British Navy to test whether they would prevent scurvy (Moberg & Chon 2000).

By means of prospective trials, it has been found that various “established” therapies can be detrimental for some diseases, while being clearly beneficial for others. This is precisely the case with hyperbaric medicine now: while a hyperoxic environment for newborn babies can lead to retrolental fibroplasia with blindness, there is also convincing evidence that hyperbaric treatments provide clear benefits in diseases such as various neurological disorders, stroke, cerebral ischemia, and wound healing. And, of course, those of us who have worked in high-altitude environments know the very short time window during which the human brain can function in hypoxic conditions. It never ceases to astonish me what a wide range of effects (benefi-

cial or toxic) a seemingly innocuous substance such as oxygen can have in various circumstances.

By and large, the experts who have made such superb contributions to the *Textbook of Hyperbaric Medicine* are the world leaders in their fields. With their help, Dr. Jain has expanded his already outstanding book into a compendium of multi-authored chapters (containing over 2,000 references) covering areas of medicine as disparate as wound healing, gastrointestinal disorders, trauma, and obstetrics. Of particular interest in this edition are the extensive discussions of cerebral circulation and its disorders, as well as of stroke, diving accidents, and neurosurgery.

For an earlier edition, Dr. Jain enlisted a remarkable Foreword by Professor Edward Teller (see next page), who began by stating “Hyperbaric medicine is new and controversial” and that we live “in an age that has the habit of treating progress with suspicion,” and then went on to pose the question, “But what is the innovator to do?” He also raised the age-old problem of the ethics of the double-blind trial, and cautioned us to be aware of the potential danger of high-pressure treatment for too long a period, in the same way that drug treatments at too high dosages bear clear risks. The field of hyperbaric medicine has indeed been subject to an at times intense debate, but much progress has been made since Professor Teller originally wrote his words (and will, I am sure, continue to be made in the future), on the basis of mutual respect, understanding, and cooperation, while also submitting beliefs to randomized trials.

Professor Teller wrote then: “It is not entirely impossible that, perhaps sometime in the next decade, professors of medicine will have difficulty in explaining why treatment with oxygen was not widely adopted much earlier.” Reflecting today on these words by an elder statesman whose scientific observations went unheeded early on, we can safely conclude that the uphill battle for acceptance of hyperbaric oxygen as therapy now rests on a solid foundation. This solid foundation is described comprehensively and clearly

within this outstanding text, in which the assembled experts provide a fair and balanced summary of the literature and evidence. And it also means that the “decade of HBO” to which Professor Teller indirectly referred has now come.

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Foreword to the Third Edition

Edward Teller[†]

Formerly Director Emeritus Lawrence Livermore National Laboratories, California & Senior Research Fellow Hoover Institution, Stanford University, Stanford, CA

Hyperbaric medicine is new and controversial. Indeed, since it is new, it must be controversial in an age that has the habit of treating progress with suspicion. But what is the innovator to do? If he applies a new and safe procedure to patients, and the procedure appears to be successful, his success might well be denigrated as anecdotal. Will he be allowed to run a double blind experiment in which half of the patients are denied the benefits of what appears to be a cure? It is an age-old problem that has grown sharper in the course of time.

Hyperbaric medicine grew out of the problems encountered by divers exposed to high pressures. The treatment of disturbances due to bubbles which develop during rapid decompression was the natural connection between high pressure and medicine. This limited application of a medical procedure is, of course, widely accepted. But its extension to counteract the damage due the air bubbles resulting from other causes, such as those accidentally introduced during medical treatment, is less generally recognized.

What is attempted in this book is a detailed and critical treatment of a large subject. If thorough discussion will lead to some consensus, the subject could grow very much larger. Indeed, oxygen, which in the form of hyperbaric oxygen (HBO) is called a drug, is the most natural of all drugs.

The first problem we must face is the danger of high pressure treatment used at excess pressure for too long a period, or in conjunction with the wrong kind of drug. Oxygen indeed has toxic effects. Furthermore, the delivery of the pressurized gas to the patient may be mishandled. A properly extensive discussion is devoted to such dangers, which are completely avoidable.

Perhaps the most natural use of HBO is to counteract carbon monoxide poisoning. The best known effect of carbon monoxide is to replace oxygen by being more firmly bound to hemoglobin. But, of course, high pressure oxygen can drive out the carbon monoxide and produce a cure in an understandable fashion.

A little harder to grasp is why pure oxygen at two atmospheres of pressure (which is ten times as concentrated as the natural occurrence) should have any general uses. Indeed, under normal circumstances, the hemoglobin in arterial blood is 97 percent saturated with oxygen. Are we exerting ourselves to supply the remaining 3 percent? The answer, of course, is no. Oxygen is also soluble in blood. At two atmospheres of pressure, oxygen can be dissolved into the plasma at several times normal levels, and can significantly improve tissue oxygenation. This is important because hemoglobin, while more eager to take up oxygen, is also more reluctant to part with it. The oxygen dissolved in the plasma, having a higher chemical potential, is pushed out from the capillaries and into the surrounding tissue. From there, it can spread small distances by diffusion.

Even in the blood itself, the dissolved oxygen may help the white blood cells in their phagocytic activity. Bacteria themselves may react in a variety of ways. It appears that many can use oxygen at normal pressures, but are damaged by oxygen at higher pressures. In the case of anaerobic bacteria, oxygen can act in a powerful way to stop the infection. In combination with other methods, HBO clearly appears effective in cases of gangrene.

But more is involved than the straightforward destruction of the pathogen. The natural healing process may also

be assisted by the presence of oxygen. This obviously should be the case when hyperbaric treatment counteracts on oxygen deficiency. Many injuries involve the destruction of capillaries, the means of delivering oxygen. Under such circumstances, healing is itself tied to revascularization of the damaged tissue. But growth of the requisite capillaries is in turn tied to the oxygen supply. This relationship can explain why in the case of many slow healing wounds, HBO seems to have a strong positive effect. Very much more can and should be done to extend the study of the speed of healing to the more normal cases.

In the human body, 20 percent of the oxygen consumption occurs in 3 percent of the body mass: the brain. This is also the region most sensitive to a deficiency of oxygen, which can produce dramatic results. Indeed, surgical methods on the carotid artery are often used to relieve oxygen deficiency to the brain. It seems logical that in HBO we have a tool that can serve a similar purpose. This might be particularly important in the case of stroke, a high-ranking cause of death and disability. It is clearly worthwhile to explore whether and to what extent disability can be reduced or avoided by prompt use of hyperbaric treatment. If the blood supply to a small region of the brain is reduced, relief might come from the diffusion of oxygen into the ischemic region from neighboring capillaries.

For all new medical techniques, scientific evidence is demanded. Yet medicine is still partly an art, as well as a dramatically advancing science. Therefore in the complicated questions of life, disease, and recovery, it is sometimes hard

to distinguish between the fight against the causes of a disease, and our efforts to aid toward the reassertion of overall health. There are good indications that HBO is helpful in many diseases, such as multiple sclerosis and osteomyelitis. One may mention these two applications because, in the former, earlier recognition of the disease made possible by the use of magnetic resonance imaging has made early treatment a better possibility, and seems to have given a real chance for help from HBO. In the latter case, osteomyelitis, the location of the disease is the bone, where oxygen is usually not amply available.

As members of the scientific community we are all naturally tempted to theorize, as long as a glimmer of a theory might be perceived. This book proceeds, however, along strictly step by step empirical lines. Case after case, the various pathologies are reviewed. In each situation, it is carefully stated to what extent the evidence merely indicates a conclusion, and to what extent the conclusion can be proved. In the present stage of HBO, it is a certainty that there will be considerable criticism. On the other hand, those who disagree are likely at the same time to disagree among themselves. I believe that the result will be not only critical reflection, but also more experimentation, more reviews, more understanding, and more progress. It is not entirely impossible that, perhaps sometimes in the next decade, professors of medicine will have difficulty in explaining why the treatment with oxygen was not widely adopted much earlier.

Preface to the Fifth Edition

K.K. Jain

American College of Hyperbaric Medicine

Almost 20 years have passed since the first edition of the *Textbook of Hyperbaric Medicine* was written, and since the publication of the 4th revised edition in 2004, there has been a considerable increase of research and development in applications of hyperbaric oxygen. Of the more than 1200 publications relevant to hyperbaric medicine during 2004–2008, approximately 300 have been selected and added to the list in this book, whilst a corresponding number of older references have been deleted to maintain the bibliography at 2000 entries. Several older publications have been retained for their historical interest, and some of these have indeed become classics.

There is an ever increasing use of hyperbaric oxygen for neurological disorders. Other areas of expansion include applications in ophthalmology and the chapter on this has been rewritten and expanded by Frank Butler and Heather Murphy-Lavoie. A new chapter by Alan Wyatt on the role

of hyperbaric oxygen in organ transplantation has been added as well as a chapter on the treatment of chronic lyme disease by William Fife and Caroline Fife.

Multimodality treatment is required in some complex disorders and hyperbaric oxygen has been combined with new advances in drug treatment and surgical procedures as well as with complementary medicine techniques such as acupuncture. As other new technologies such as those for manipulating stem cells develop, their interaction with hyperbaric oxygen is being studied. Hyperbaric oxygen may prove to be a useful adjunct to stem cell-based therapeutics and regenerative medicine.

I would like to thank the editorial staff at Hogrefe & Huber Publishers, particularly the Publishing Manager, Robert Dimbleby, for their help and encouragement during this revision.

Preface to the Fourth Edition

K.K. Jain

American College of Hyperbaric Medicine

The textbook has been revised in accordance with the progress made in hyperbaric medicine during the past four years. There were over 1000 publications relevant to hyperbaric medicine during 1999–2002. Approximately 200 of these were selected and a corresponding number of older references were deleted to keep the total number of references in the bibliography to 2000. The number of clinical trials for various applications in hyperbaric oxygen therapy has increased. These are included wherever the published results are available. As personalized medicine is developing, it will be applied to hyperbaric oxygenation as well. It is already obvious that patients require an individualized approach in hyperbaric therapy protocols. The dose of ox-

xygen, pressure, and duration of treatment need to be determined for each patient individually. It is difficult to reach any conclusions from clinical trials about a particular pressure of oxygen or even a range for a broad diagnostic category with many variants among patients that determine the response.

Applications in neurological disorders are developing further and space devoted to this area has been increased. A new chapter by Neubauer and Harch has been added on the treatment of cerebral palsy with hyperbaric oxygenation.

I wish to thank the publishing directors of Hogrefe Publishers and their Editor, Mr. Robert Dimbleby, for their help and encouragement throughout the period of revision.

Preface to the Third Edition

K.K. Jain

American College of Hyperbaric Medicine

Hyperbaric medicine continues to make progress. The textbook has been revised and expanded with inclusion of new contributors. We are fortunate to have an article from Prof. Hideyo Takahashi of Japan describing the state of development of hyperbaric oxygen therapy in Japan.

As in the previous edition, objective judgment has been exercised in deciding to include various reports and studies on this subject. There are more than 200 publications every year on hyperbaric medicine, and all the publications cannot be included in references. The bibliography already contains more than 2000 entries. Most of the older references have been retained because of their historical value.

Much of the original material still holds its value and has also been retained. Simply because no new work has been done in some areas does not mean that these indications for HBO are no longer valid. Research in hyperbaric medicine continues to be limited by lack of funding. However,

the technique is available for clinical application in certain cases when the need arises and often a precedence in that area helps. Well-documented anecdotal reports have a teaching value, and this has been utilized in the textbook. This is particularly so in the case of emergency medicine and treatment of hypoxemic/ischemic encephalopathies, where it would be practically impossible to conduct controlled studies.

Much of the expansion of hyperbaric oxygen therapy is in the area of neurological disorders, which is reflected in the increased number of chapters devoted to this area. This application of hyperbaric oxygen holds the greatest promise for the future for diseases of the nervous system.

I wish to thank the publishing directors of Hogrefe & Huber and their Editor, Mr. Robert Dimbleby, for their help and encouragement throughout the period of preparation.

Preface to the Second Edition

K.K. Jain

American College of Hyperbaric Medicine

A great deal of progress has taken place in Hyperbaric Medicine since the publication of the first edition. This has necessitated a thorough revision of the book and inclusion of new contributors. Some of the outdated references were removed and new ones have been added, bringing the total about 1800 entries. I have tried to keep my judgment objective and this is helped by the fact I have no involvement in the political and financial aspects of hyperbaric medicine.

In spite of this critical revision and corrections, I am pleased to state that a great deal of the old stuff still holds its value. Use of hyperbaric oxygen therapy in neurological disorders continues to expand and required a chapter on

neurosurgery, for which I was fortunate to have the collaboration of Dr. Michael Sukoff of the United States, who has done much of the pioneer work in this field. The chapter on pediatric surgery by Prof. Baydin from Russia is a useful new addition. With the inclusion of unpublished work on the role of neuropeptides in oxygen therapy (Prof. G.T. Ni) from China, the book is now truly international.

I wish to thank the publishing directors of Hogrefe & Huber Publishers for their help and encouragement throughout the period of revision. Countless other colleagues also helped and their names are too numerous to list here.

Preface to the First Edition

K.K. Jain

American College of Hyperbaric Medicine

This book goes considerably beyond the scope of the *Handbook of Hyperbaric Oxygen Therapy*, which was written by me, and published by Springer Verlag in 1988. In addition, with the many rapid developments in this field, the *Handbook* has already become remarkably outdated. Our use of the word “textbook” in the title of the present work is in keeping with the increasing worldwide recognition of this branch of medicine, and the need for a definite and inclusive source covering this body of knowledge, as it exists today.

In practice hyperbaric medicine of course involves mostly the use of hyperbaric oxygen, i.e., oxygen under pressure greater than atmospheric. As a result, this field overlaps with diving medicine in the areas of

- the effect of high pressure on the human body
- physical exercise under hyperbaric environments
- air embolism
- decompression sickness

I have made no attempt to intrude any further into diving medicine, as there are several excellent textbooks on that subject. In addition, the use of normobaric oxygen has been

discussed elsewhere in a 1989 title by K.K. Jain, *Oxygen in Physiology and Medicine*.

I have written this current work in a textbook style, and there is more discussion on the pathophysiology of diseases and the rational basis of hyperbaric oxygen than in the *Handbook*. Extensive and up-to-date references have been assembled as an integral part of this project, and these total about 1,500.

The highlights of this present effort are the newly documented effectiveness of hyperbaric oxygen therapy in the rehabilitation of stroke patients, and the validation of these gains via the iofetamine scan technique. This same method has also been used to document the improvement in multiple sclerosis patients undergoing hyperbaric oxygen therapy.

In the preparation of this work I was considerably aided by the capable and cooperative management effort provided by the two directors of the Hogrefe & Huber publishing company. The execution of a project involving this degree of both scope and detail is certainly an exercise in teamwork between author and publisher, and it was a pleasure to have shaped the production in a creative and timely manner.