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Review article

HISTORICAL DEVELOPMENT OF THE HYPERBARIC OXYGENATION

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ABSTRACT:

Background: Hyperbaric oxygenation (HBO) is a treatment in which a patient breathes near 100% oxygen within a chamber at a pressure greater than one atmosphere absolute (ATA). The development of hyperbaric medicine is continuous and associated with the history of underwater activities, the development of physical laws and physiological mechanisms of breathing.

Purpose: The aim of this article is to present the development of hyperbaric oxygenation internationally and nationally.

Materials and Methods: We have conducted a literature review of the published works on hyperbaric oxygen therapy (HBOT) during the last 100 years. Our survey includes scientific reports and books in English and Bulgarian.

Results: Three main periods of the historical development of HBOT can be defined. In the past, HBO did not have much scientific support but is extensively used in the field of medicine. We observed an increase in scientific interest in HBO during the last two decades both in our country and worldwide. The majority of the reviewed articles contained information about different aspects of HBO as clinical uses, effects, risks. HBOT has been used as a primary and adjuvant treatment for a variety of diseases for nearly 50 years in Bulgaria. The main areas of application and researches of hyperbaric oxygen therapy include diving diseases, intoxications, traumatic injuries, soft tissue infections, diabetic foot, hearing loss, some neurological disorders, etc.

Conclusion: Over the past decades, hyperbaric oxygen therapy has grown rapidly worldwide in accordance with evidence-based medicine methods, and future developments to expand the knowledge are perspective.

Keywords: hyperbaric medicine, hyperbaric oxygen therapy, oxygenation, Bulgaria,

INTRODUCTION

More than a century ago, hyperbaric medicine was emerging as an independent branch in medical science. The presence of a large number of diseases, which underlie hypoxia, determines its development and widespread use since hyperbaric oxygenation (HBO) reduces or eliminates all forms of oxygen deficiency in the body [1].

Hyperbaric oxygenation (HBO) is a clinical method of treatment with high pressure oxygen. When breathing oxygen under pressure exceeding 1 atmosphere, i.e. in HBO, it is possible to significantly increase oxygen supply to cells affected by hypoxia. The result is a positive therapeutic effect in the treatment of many diseases [1, 2].

The historical development of hyperbaric medicine has been closely linked with the development of underwater activity since ancient times. Scientific discoveries and knowledge about the physical laws and physiological mechanisms of oxygenation at elevated atmospheric pressure later became the basis of hyperbaric medicine [2].

The purpose of this article is to review the development of "hyperbaric oxygenation" internationally and nationally, tracing available literature sources from ancient times to the present day.

The term "hyperbaric" is derived from its two constituents. The first "hyper-" (of Greek origin) means "above", "more than usual", and the second "baric" refers to pressure (from the Greek *"barys"*). Typically, the term is associated with a pressure higher than normal, for example, a "hyperbaric chamber", i.e. pressure vessel or "hyperbaric oxygen" [3].

According to Merriam-Webster universal dictionary, the term "hyperbaric" in the meaning defined as "of, relating to, or utilizing greater than normal pressure especially of oxygen," began to be used in 1962 [4]. This is evidenced by various scientific publications from this period by Boerema, Brummelkamp, Meijne, Smith et al., Illingworth, on the therapeutic effects of hyperbaric oxygen in cardiac surgery, in carbon monoxide poisoning and in severe anaerobic infections [5, 6, 7].

Oxygen (O_2) is a chemical element with the number 8 in the Mendeleev table. Oxygen (*oxygène* in French) is a colorless, odorless and tasteless gas that constitutes about 21% of the air and is required for the respiration and combustion processes. The therapeutic use of oxygen was first described in T. Beddoes's scientific work in 1794 [8].

The term "oxygenation" is defined as the process of adding oxygen to a physical or chemical system, e.g. oxygenation of the blood (med.) [9]. In this sense, the term has been used since 1788, after French chemist Antoine Lavoisier established the role of oxygen in combustion and respiration, independently of Joseph Priestley and Carl Scheele.

The use of high-pressure oxygen in clinical settings for therapeutic purposes is commonly referred to by vari-

ous terms (synonyms) in the scientific literature: oxybarotherapy, oxygen barotherapy, hyperbaric oxygen therapy, treatment with high oxygen pressure, recompression therapy, etc. The most commonly used term is "hyperbaric oxygen therapy" or "hyperbaric oxygenation" in both foreign and Bulgarian scientific literature. The use of the term "oxybarotherapy" has been noted in particular publications (of Russian and Polish authors) but without implying a different meaning in the term [10, 11].

In the European code of good practice for HBOT, hyperbaric oxygen therapy is defined by three essential elements: breathing oxygen, increased ambient pressure, and a hyperbaric chamber. A hyperbaric therapy chamber is a pressure vessel capable of accommodating one or more persons with the purpose of providing medical treatment. Two kinds of hyperbaric therapeutic chamber exist: multiplace chamber (for two or more persons) and monoplace chambers (for a single patient) [12].

The Undersea and Hyperbaric Medical Society (UHMS) defines hyperbaric oxygenation as "an intervention in which a person breathes near 100% oxygen intermittently into a hyperbaric chamber that is pressurized above sea level, i.e. above 1 absolute atmosphere (1 ATA equal to 101,325 kPa). For clinical purposes, the pressure should be equal to or higher than 1.4 ATA while breathing oxygen [13]. The first report of the UHMS Committee was published in 1977, updated periodically and served as guidance for practitioners and scientists interested in HBO and for insurance coverage purposes as well.

Historical development

F. Wattle [2] highlights three periods in the historical development of Hyperbaric Medicine, which also correspond to the development of the concept of hyperbaric medicine:

1. Period of discoveries: from the Renaissance to the Age of Enlightenment in the 18th Century.

2. Period of hyperbaric therapy: from the middle of the 19th century to the beginning of the 20th century.

3. Modern period of Hyperbaric Medicine and practice based on scientific methods and evidence: from the second half of the 20th century to the present.

The **first period** was featured by remarkable scientific and technical progress: E. Torricelli (a student of Galileo Galilei) invented the mercury barometer in 1643; in 1653, B. Pascal confirmed the variation of atmospheric pressure and established the laws of hydrostatics; Boyle (1661) and Mariotte (1676) formulated the law of the relationship between volume and pressure of the ideal gas; in 1755 Black discovered carbon dioxide; J. Priestley discovered oxygen in 1775, and in 1789 A. Lavoisier described the oxidative phenomenon. During this period, various methods and tools for underwater activities were developed. In 1662, the English physician Henshaw used a spherical wooden chamber ("domicilium") with compressed air to treat pulmonary and gastric diseases [1, 2].

The **second period** in the development of hyperbaric medicine began in the mid-nineteenth century. The introduction of compressed air therapy into medical practice is the work of three French doctors: Junod (1834, Paris), Tabarie (Montpellier) and Pravaz (Lyon). Each of them constructed their own chamber, carried out observation and treatment of different categories of patients. In 1841, the French engineer Jean Triger created a caisson chamber for high pressure work in the construction of tunnels and bridges. In a report published in 1854, the French physicians' Pol and Watelle described the clinical manifestations of so-called caisson disease (decompression sickness). Thus in 1873, American surgeon Andrew Smith applied therapeutic recompression to caisson disease in a treatment chamber constructed by him [14]. In 1855, the first edition of the book by Bertin, "Clinical study of the application and action of compressed air in the treatment of various diseases", was published in Paris. Subsequent clinical observations were published by Sandhal (Stockholm, 1862), Tutshek (Nice, 1863), Vivenot (Johannesberg, 1868) and other authors. The classic book by Paul Bert "Barometric Pressure: Experimental Physiological Research" [15], was published in Paris in 1878 and was awarded by the French Academy of Sciences. He studied the effects of hyperbaric oxygen and discovered its toxic effects on living organisms. Bert's work is fundamental for contemporary pressure physiology and in hyperbaric medicine, as well as in underwater and aerospace activities and research [2, 16].

The available literature on hyperbaric therapy up to 1887 was summarized by A. Arntzenius in his monograph published in the same year. The monograph examines the therapeutic effect of air under elevated atmospheric pressure and contains a bibliographic list of nearly 300 reference titles [17].

In England, at that time, the first scientific approach to using hyperbaric therapy was by the respiratory physiologist John Scott Haldane. In 1908 The British Admiralty published his decompression tables, which with some variations are used so far. In 1895, Haldane experimentally demonstrated the effect of hyperbaric oxygen on carbon monoxide poisoning [18]. Behnke, Bennett, Bean, Hill, Saltzman [19, 20, 21] also have a significant contribution in studying the effects of the increased pressure of gas environment on the human body. In 1927, in Cleveland, Cunningham built the largest chamber in the world, which existed until the mid-1930s [16].

From the mid-twentieth century began the **third period** in the development of HBO as a modern science with the publication of the results of the Dutch surgeon Boerema. In 1959, Boerema performed cardiac surgery in a large hyperbaric chamber in Amsterdam. In 1961, Boerema and Brummelkamp reported the beneficial effect of HBO in treating anaerobic infection and gas gangrene. Among the pioneers of modern hyperbaric oxygenation are Ledingham (UK) and Jacobson (USA). A number of scientists and clinical practitioners in various specialties have been researching and contributing to the development and validation of HBO using scientific methods [1, 2, 5].

Since its inception in the 1950s, hyperbaric oxygenation has been in a period of intense development over the next two decades - over 60 indications have been described. Between 1980 and 1994, there was a period of doubt and new research questions about the utility and

widespread use of hyperbaric oxygenation. This leads to steps to refine the indications and major aspects of hyperbaric therapy and to establish it as a scientific discipline. In the context of the modern development of HBO as evidence-based medicine, over the past 25 years, basic indications for the treatment of HBO through consensus decisions have been adopted by a special jury. They are based on significant positive results from experimental and clinical studies conducted with strict adherence to the Evidence Based Medicine methodology and procedures [2, 22, 13].

The review of numerous publications referenced in the Medline database since 2000 shows that the number of experimental and clinical studies and the number of hyperbaric publications have increased, which creates new perspectives for researchers. Despite the accumulated experience and efforts to provide high quality clinical trials in modern hyperbaric medicine, not all indications of HBO are supported by the highest level of scientific evidence. In medical practice, however, decisions are very often based on a certain level of facts, which is less than absolute proof. As mentioned in the report of the European Committee for Hyperbaric Medicine (2017), there are clinical situations in which it is extremely difficult or impossible to conduct high quality controlled studies, for example: the use of HBO in decompression sickness or arterial gas embolism is accepted as a universal remedy, and it would be inappropriate for a patient to not receive this treatment for the purposes of the study; there are diseases or conditions that are too complex, with many variations, that would be difficult to create an appropriate study design to evaluate each procedure. Often the hyperbaric experts report and reach a consensus based on their own experience and significant literature data [22].

HBO is used in a variety of diseases and conditions. The indications for this treatment may vary by professional and scientific hyperbaric organization. A few countries have developed recommendations for HBOT use. The list of indications published by the European Committee on Hyperbaric Medicine (ECHM) and the United States Society for Underwater and Hyperbaric Medicine (UHMS) was last updated respectively in 2017 and in 2019. The indications are evaluated and validated by experts on the basis of their own experience and a summary of the scientific evidence in hyperbaric medicine (Table 1).

Table1. Accepted clinical indications for HBOT according ECHM and UHMS

European Committee for Hyperbaric Medicine (ECHM) Recommendations on accepted HBO indications according to the level of supporting evidence	**Undersea and Hyperbaric Medical Society (UHMS)** Approved HBO Indications
Type 1 "strongly recommended"as a primary treatment method CO poisoning Decompression illness Gas embolism Anaerobic or mixed bacterial infection Open fracture with crush injury Prevention of osteoradionecrosis after dental extraction Osteoradionecrosis (mandible) Soft tissue radionecrosis (cystitis, proctitis) Sudden deafness **Type 2 "recommended"** Diabetic foot lesions Femoral head necrosis Compromised skin grafts and flaps Central retinal artery occlusion (CRAO) Crush injury without fracture Osteoradionecrosis (bones other than mandible) Radio-induced lesions of soft tissue Surgery and implant in irradiated tissue Ischaemic ulcers Refractory chronic osteomyelitis Burns, 2nd degree more than 20% BSA Pneumatosiscystoidesintestinalis Neuroblastoma, stage IV **Type 3 "optional"** Brain injury (TBI, chronic stroke, post anoxic encephalopathy) in selected patients Radio-induced lesions of larynx	1. Air or Gas Embolism 2. Arterial Insufficiencies A. Central Retinal Artery Occlusion B. Hyperbaric Oxygen Therapy for Selected Problem Wounds 3. Carbon Monoxide Poisoning 4. ClostridialMyonecrosis (Gas Gangrene) 5. Compromised Grafts and Flaps 6. Acute Traumatic Ischemias 7. Decompression Sickness 8. Delayed Radiation Injuries (Soft Tissue and Bony Necrosis) and Potential for Future Research 9. Sudden Sensorineural Hearing Loss 10. Intracranial Abscess 11. Necrotizing Soft Tissue Infections 12. Refractory Osteomyelitis 13. Severe Anemia 14. Adjunctive Hyperbaric Oxygen Therapy in the Treatment of Thermal Burns

Radio-induced lesions of the CNS Post-vascular procedure reperfusion syndrome Limb replantation Selected non-healing wounds secondary to systemic processes Sickle cell disease Interstitial cystitis	

Hyperbaric oxygenation in Bulgaria

The development of hyperbaric medicine in Bulgaria began in the early 1960s when the first non-professional diving training sessions were carried out. Existing data shows that for the period from its inception to the end of the twentieth century, the development of hyperbaric medicine in Bulgaria is mainly related to the diving activity and within the framework of the military-medical provision of the country. The first physicians with specialized training in hyperbaric and diving medicine actively participated in research programs, underwater experiments and competitive sport diving [23, 24].

For the first time in Bulgaria, hyperbaric oxygenation as a clinical method was used at the Military Medical Academy - Sofia in 1967. Two years later, hyperbaric oxygenation was applied in the chamber of a division of Navy submarines. In 1975, a chamber complex began operating at the Institute of Oceanology of the Bulgarian Academy of Sciences, where an experimental activity, recompression therapy and hyperbaric oxygenation were performed. In the 1990s, the clinical application of HBO was carried out at the Naval Hospital - Burgas (for a certain period of time) and at the Naval Hospital - Varna (from 1992 until now). In 2003, the Oxygen Hyperbaric Medical Center was established, equipped with multiplace chambers, thus contributing to the development and wider use of HBO therapy in the country [24].

Since 2000 the scope of application of hyperbaric oxygenation in clinical practice in Bulgaria has been expanding, as evidenced by the larger number of scientific publications on the topic. The analysis of the literature shows that data from retrospective studies and presentation of individual clinical cases in the field of hyperbaric oxygenation in Bulgaria predominate. The main areas of research are HBO application in clinical toxicology, diving, surgery, neurology, and hearing loss. A number of publications have demonstrated the experience in HBO treatment of acute carbon monoxide and smoke gases poisoning, ethyl and methyl alcohol, phalloidin mushroom poisoning, psychoactive drugs, petroleum products, organic solvents, pesticides, spiders, etc. Results of HBO use in severe burns and plastic surgery have also reported. Despite its successful use, HBO is used in a very small percentage of the total number of patients with various poisonings and toxicities [25, 26, 27, 28].

Some of the HBOT therapeutic effects include: stimulation of the phagocytic function of neutrophils and angiogenesis, reduction of inflammation and hypoxia, suppression of toxin production, improved antibiotic activity, which are important to fight severe anaerobic and mixed soft tissue infections. The results of using HBO as adjuvant therapy in non-healing wounds of different origin and in the diabetic foot have been reported by a number of Bulgarian authors [29, 30, 31]. We found the publication of studies of HBO use in the complex treatment of neurosensory hearing loss in our country [32, 33].

Successful clinical application of HBO in orthopedics and traumatology as adjunctive therapy in severe cases of crush syndrome, open fractures, post-traumatic ischemic conditions, osteomyelitis, and aseptic osteonecrosis, has been reported by Gaevski [34], Krumov et al. [35].

Over the last decade, there has been an increasing number of scientific publications and books in the Bulgarian literature related to HBO treatment of diving diseases [36, 37, 38].

For the last few years, there has been interesting in applying hyperbaric oxygenation in the treatment of some investigational or controversial indications, for example, cerebral palsy and autistic spectrum disorders. Several authors, e.g. Chavdarov, Bozov et al., have investigated the effect and therapeutic potential of hyperbaric oxygen therapy on symptoms and developmental growth of children with cerebral palsy or autism [39, 40].

CONCLUSION

Based on the literature reviewed, we summarized the basic concepts and stages in the historical development of hyperbaric medicine. Over the past decades, hyperbaric oxygen therapy has grown rapidly worldwide in accordance with evidence-based medicine methods, and future developments to expand the knowledge are perspective.

Abbreviation list:

HBO – hyperbaric oxygenation
HBOT – hyperbaric oxygen therapy
ECHM – European Committee for Hyperbaric Medicine
UHMS – Undersea and Hyperbaric Medical Society

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