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Review Article / Derleme

Sports injuries and hyperbaric oxygen therapy: physiological effects and previous findings

Spor yaralanmaları ve hiperbarik oksijen tedavisi: fizyolojik etkiler ve önceki bulgular

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ABSTRACT

Problems encountered in the management of sports injuries can lead to a prolonged treatment process and a long period of time away from sports that may cause significant economic loss, as well. To ensure the most effective return to sports, a multidisciplinary approach is often required.

Research has demonstrated that hyperbaric oxygen therapy (HBOT) shows promising results as a treatment modality for sports injuries. A search of the scientific literature was conducted using the keywords "hyperbaric oxygen therapy" and "sports injuries" across PubMed, Cochrane Library, and Web of Science databases. The positive effects of HBOT have been reported in the treatment of various sports injuries, including muscle and soft tissue injuries, as well as bone marrow edema.

This review examines the physiological effects of hyperbaric oxygen therapy, as well as the findings obtained from animal injury models and human clinical studies on its use in sports injuries. The effects of HBOT vary depending on the type of injury, and it is generally more beneficial as an adjunctive treatment rather than as a standalone therapy.

Although numerous studies have been published, a standardized treatment protocol has yet to be established. However, based on current protocols in the literature, it is believed that a 90- to 120-minute treatment session, administered at least five days per week at 2.0-2.5 ATA, will provide the greatest benefit. The total number of sessions should be determined by the physician following the treatment, based on the patient's specific condition and needs.

Keywords: *Hyperbaric oxygen therapy, sports Injuries*

ÖZ

Spor yaralanmalarının yönetiminde karşılaşılan sorunlar tedavi sürecinin uzamasına ve spordan uzun süre uzak kalınmasına yol açabilir. Bu durum önemli ölçüde ekonomik kayba neden olabilir. Spora dönüş sürecinin en iyi şekilde tamamlanabilmesi sıklıkla multidisipliner bir yaklaşım gerektirmektedir.

Yapılan araştırmalar, hiperbarik oksijen tedavisinin spor yaralanmalarında bir tedavi yöntemi olarak umut verici sonuçlar sunduğunu göstermektedir. Bilimsel literatür, PubMed, Cochrane Library ve Web of Science veritabanları aracılığıyla "hyperbaric oxygen therapy" ve "sports injuries" anahtar sözcükleriyle taranmıştır. Kas ve diğer yumuşak doku yaralanmaları ile kemik iliği ödemi gibi pek çok spor yaralanmasında hiperbarik oksijen tedavisinin olumlu etkileri raporlanmıştır.

Bu derlemede, hiperbarik oksijen tedavisinin fizyolojik etkileri ile spor yaralanmalarına ilişkin çalışmalarda kullanılan hayvan modelleri ve insan klinik çalışmalarının sonuçları incelenmiştir. HBO2'nin etkisi, yaralanma türüne göre değişmekte olup, tek başına bir tedavi yöntemi olarak değil, daha çok yardımcı bir tedavi olarak yarar sağlamaktadır. Literatürde birçok çalışma bulunmasına rağmen, standart bir tedavi protokolü henüz oluşturulmamıştır. Ancak, literatürdeki mevcut protokoller göz önünde bulundurulduğunda, 2,0-2,5 ATA'da haftada en az 5 gün uygulanan 90 veya 120 dakikalık bir tedavi protokolünün en iyi yararı sağlayacağı düşünülmektedir. Toplam seans sayısı, hastanın durumu göz önünde bulundurularak tedavi sürecini izleyen hekim tarafından belirlenmelidir.

Anahtar Sözcükler: *Hiperbarik oksijen tedavisi, spor yaralanmaları*

INTRODUCTION

Competing in sports involves significant engagement of various body parts. The pressure to succeed often leads athletes to train without being adequately physically prepared for competitions. Insufficient recovery and improper training can result in decreased performance, fatigue, and an increased risk of injury (1). The approach of the sports physician to injury management plays a critical role in an athlete's ability to resume regular activity. Failure to promptly diagnose and properly manage sports injuries can lead to extended absences from athletic activities. This can also result in substantial financial costs for both amateur and professional sports (2).

Fair and Champa estimate that eliminating contact in college sports could save up to $18.4 billion annually (3). In the English Premier League, injury-related performance declines lead to losses of approximately £900 million GBP each

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season (4). In the Netherlands, sports injuries cost over €3 billion per year (5).

The management of sports injuries often requires a multidisciplinary approach to ensure that athletes can return to training as quickly as possible. Research indicates that hyperbaric oxygen therapy shows considerable promise in the management of sports injuries (6,7). Many elite athletes from diverse sports, including tennis, swimming, basketball, and golf, have reported using hyperbaric oxygen therapy as part of their recovery (8).

Hyperbaric Oxygen Therapy

Hyperbaric Oxygen Therapy (HBOT) involves the intermittent administration of 100% oxygen at a pressure greater than one atmosphere absolute (ATA) in a closed chamber. For the treatment to be clinically effective, the pressure must be at least 1.4 ATA, though the typical range is between 2.0 and 3.0 ATA. According to the Undersea and Hyperbaric Medical Society (UHMS), for a treatment to be classified as hyperbaric oxygen therapy, the pressure must exceed 2.0 ATA. Treatment duration can be adjusted based on the patient's condition, typically lasting between 90 and 120 minutes. Patients breathe oxygen through a mask, hood, or endotracheal tube, in either a single or multi-patient chamber (9). The indications approved by UHMS and recommended by the European Committee on Hyperbaric Medicine are listed in Tables 1 and 2.

Table 1. UHMS HBO_2 Indications

Air or Gas Embolism	Carbon Monoxide Poisoning
Central Retinal Artery Occlusion	Decompression Sickness
Clostridial Myonecrosis (Gas Gangrene)	Acute Traumatic Ischemia
Compromised Grafts and Flaps	Sudden Sensorineural Hearing Loss
Delayed Radiation Injuries	Thermal Burns
Intracranial Abscess	Avascular Necrosis*
Necrotizing Soft Tissue Infections	
Refractory Osteomyelitis	
Severe Anemia	

* Recently added as an indication in the new version of the UHMS indication list

Table 2. Recommendations on the HBO_2 indications accepted for European Consensus (5)

Type 1	Type 2	Type 3
CO poisoning	Crush injury without fracture	Brain injury (acute and chronic TBI, chronic stroke, post anoxic encephalopathy) in highly selected patients
Open fractures with crush injury	Osteoradionecrosis (bones other than mandible)	Radio-induced lesions of larynx
Prevention of osteoradionecrosis after dental extraction	Radio-induced lesions of soft tissues (other than cystitis and proctitis)	Radio-induced lesions of the CNS
Osteoradionecrosis (mandible)	Surgery and implant in irradiated tissue (preventive treatment)	Post-vascular procedure reperfusion syndrome
Soft tissue radionecrosis (cystitis, proctitis)	Ischemic ulcers	Limb replantation
Decompression illness	Refractory chronic osteomyelitis	Selected non-healing wounds secondary to systemic processes
Gas embolism	Burns, 2nd degree more than 20% body surface area	Sickle cell disease
Anaerobic or mixed bacterial infections	Pneumatosis cystoides intestinalis	Interstitial cystitis
Sudden deafness	Neuroblastoma, stage IV	
Diabetic foot lesions		
Femoral head necrosis		
Compromised skin grafts and musculocutaneous flaps		
Central retinal artery occlusion		

Type 1 = strongly recommended, Type 2 = recommended, Type 3 = possible/optional

Physiological Effects of HBO_2 on Sports Injuries

The plasma oxygen concentration at sea level is approximately 3 ml/l (10). Under standard perfusion conditions, tissues require about 60 ml/l of oxygen at rest to maintain normal cellular metabolism. Without the contribution of oxygen bound to hemoglobin, dissolved oxygen at a pressure of 3 ATA is nearly sufficient to meet the resting total oxygen requirement of many tissues (11). By increasing PaO2, hyperbaric oxygen therapy (HBOT) promotes the proliferation of endothelial progenitor cells, neoangiogenesis, and neovascularization (12). Additionally, HBOT reduces cellular ischemia and edema and induces vasoconstriction by raising the concentration of extracellular oxygen (13).

HBOT also stimulates the mobilization of hypoxia-inducible factor 1-α, vascular endothelial growth factor (VEGF), stromal-derived factor 1, and bone marrow-derived stem cells (CD34), while reducing neutrophil adhesion through modification of integrin β-2, which helps attenuate ischemia-reperfusion injury (14-17). Furthermore, HBOT enhances cell growth and modulates the inflammatory response by increasing the production of reactive oxygen species (ROS) and reactive nitrogen species. This leads to improved vasculari-

zation and better tissue survival following ischemia. ROS play a crucial role in multiple pathways that facilitate neoangiogenesis and vasculogenesis, both of which are mediated by hypoxia-inducible factors (18,19).

Following muscle damage, inflammation is marked by the generation and release of inflammatory cytokines, increased vascular permeability, neutrophil migration, and edema (20). HBOT helps reduce edema through improved homeostatic processes and vasoconstriction. Moreover, by reducing tissue damage and inhibiting leukocyte adhesion to the endothelium, HBOT enhances leukocyte motility and improves microcirculation (21). HBOT accelerates the transition from the inflammatory to the proliferative phase (7). Horie et al. found that HBOT treatment accelerated satellite cell proliferation and myofiber maturation (22). Similarly, Oyaizu et al. reported that HBOT increased the number of proliferating and differentiating satellite cells, as well as regenerating muscle fibers (23).

Complications

Complications of HBO2 are typically oxygen- or pressure-related and most often include barotrauma or oxygen toxicity affecting the central nervous system or pulmonary systems. Rarely, symptoms such as weakness, dizziness, hypoglycemia, and vision problems (e.g., reversible myopia) may occur. The most common complication is **middle ear barotrauma**. In a study involving 62,614 HBO2 sessions with 2,334 patients, middle ear barotrauma occurred in 9.2% of patients and 0.04% of sessions. Other complications, such as hypoglycemia, oxygen toxicity, dizziness, anxiety reactions, shortness of breath, and chest pain, were reported in 0.5%-1.5% of patients (24).

Evaluating patients for potential risks before initiating HBO2, taking precautions to prevent complications, and closely monitoring patients during treatment are critical for enhancing safety. Most adverse events can be effectively prevented or managed with simple measures. From this perspective, HBO2 is considered one of the safest medical treatments. It is also important to note that patients undergoing HBO2 often have multiple comorbidities, which may increase their risk of complications. Conversely, healthy individuals have a significantly lower likelihood of experiencing adverse effects.

WADA's Stance and Potential Risks for Athletes

In 2006, the World Anti-Doping Agency (WADA) banned the use of HBO2 under the category of oxygen transfer enhancement. However, due to insufficient evidence supporting its potential to enhance performance, WADA reclassified supplemental oxygen as permitted in 2009. In 2016, it was further clarified that supplemental oxygen was allowed only via inhalation (25).

It is important to note that WADA may revise its stance or impose additional restrictions-such as limits on pressure or duration-if future evidence reveals new effects of HBO2.

Moreover, although rare in healthy individuals, there is always a possibility of complications arising from HBO2 use. Experiencing any severe complications could delay an athlete's return to the field.

HBO2 Application in Different Types of Sports Injuries

Muscle Injuries

Muscle injuries encompass a wide range of conditions, including muscle strains, muscular contusions, delayed-onset muscle soreness, and muscle cramps (26). According to a study conducted between 2009 and 2015 on collegiate athletes, muscle strains were the second most common cause of sports suspension lasting more than 21 days (27).

Research on animals by Best et al. demonstrated that HBO2 therapy promotes both morphological and functional recovery after acute muscular stretch injuries (28). Another animal study found that rats treated with HBO2 following a muscular contusion exhibited lower levels of creatine kinase-an indicator of muscle injury-and an increase in muscle weight (29).

HBO2 is beneficial not only for treating sports injuries but also for alleviating sports-related fatigue. During the Nagano Winter Olympics, Ishii and colleagues reported using HBO2 as a recovery method for muscular fatigue. Their findings revealed that athletes who underwent HBO2 therapy at a pressure as low as 1.3 ATA (approximately 11 feet below sea level) for short sessions of 30-40 minutes (averaging two sessions, with a maximum of six) experienced faster recovery times (30).

Additionally, other studies have shown a significant reduction in blood lactate concentration and notable improvements in maximal oxygen consumption and oxygen consumption at the anaerobic threshold following HBO2 therapy (31, 32).

As previously reported in the literature, HBO2 may also be effective in treating delayed-onset muscle soreness (DOMS). DOMS is characterized by soreness in skeletal muscles following intense exercise, typically resolving within 5-7 days (7). However, DOMS can lead to a temporary decline in physical performance and an increased risk of injury (33, 34). HBO2 has been shown to enhance muscle strength, reduce pain, and accelerate recovery in individuals with DOMS.

Webster et al. investigated the effects of HBO2 on recovery from exercise-induced muscle damage in a study involving

12 healthy males (35). Muscle damage was induced through calf raises performed to failure. Participants were divided into two groups: one received HBO2 therapy (2.5 ATA with 100% oxygen for 60 minutes), while the other received a placebo (1.3 ATA with air). Treatments were administered at 3-4 hours, 24 hours, and 48 hours post-exercise. In the placebo group, isometric peak torque declined from baseline on days 1 and 2, whereas no such decline was observed in the HBO2 group. By day 5, the HBO2 group reported significantly lower levels of pain and soreness compared to the placebo group.

Staples et al. conducted the largest study on HBO2 and DOMS, involving 66 untrained males, and demonstrated that HBO2 significantly accelerated recovery in athletes (36). In this study, DOMS was induced in the non-dominant quadriceps, and pain and muscle torque were measured before, during, and after HBO2 therapy. Participants were divided into four groups: HBO2, delayed HBO2, sham treatment, and control.

The HBO2 group received 100% oxygen at 2.0 ATA for one hour at 0-, 24-, and 48-hours post-exercise, followed by sham treatments at 72 and 96 hours. The sham treatment group received 21% oxygen at 1.2 ATA for the same duration. The delayed HBO2 group underwent sham treatments at 0- and 24-hours post-exercise, followed by HBO2 therapy at 48, 72, and 96 hours. Results showed that the HBO2 group exhibited significantly improved muscle torque compared to the other groups.

Harrison et al. investigated the use of HBO2 for treating exercise-induced muscle injuries in 18 untrained, college-aged males (37). Participants were divided into three groups: immediate HBO2, delayed HBO2, and control. Muscle injury was induced in the non-dominant arm using preacher curls. The immediate HBO2 group received oxygen therapy shortly after exercise and for the next four days, while the delayed group initially received sham treatments and began HBO2 therapy later. Measurements included creatine kinase levels, muscle strength, soreness, and MRI scans. The study found no significant differences between the groups in any measure, suggesting that HBO2 therapy did not facilitate soft tissue injury recovery. However, the authors cautioned that their findings might not fully apply to soft tissue athletic injuries due to the study's limitations. They suggested that HBO2 could be more effective for injuries involving more extensive soft tissue damage or where oxygen availability is significantly compromised by the injury's location or severity of edema.

Babul et al. also explored the effects of intermittent HBO2 on exercise-induced muscle damage in 16 females (38). Participants were divided into HBO2 and control groups and subjected to 300 maximal eccentric contractions on the non-dominant leg, performed in 30 sets of 10 repetitions with 15-second rests between sets. The HBO2 group received 100% oxygen at 2 ATA for 60 minutes, while the control group was exposed to 1.2 ATA with air. Four treatment sessions were conducted over four days. Measurements included muscle soreness, eccentric strength, quadriceps circumference, creatine kinase, malondialdehyde, and muscle signal intensity via MRI. No significant differences were observed between the groups. Presti et al. later noted that the small sample size limits the generalizability of these findings (39).

In contrast, Chen et al. studied 41 baseball players already experiencing exercise-induced muscle soreness or grade I muscle strain in their extremities (40). Participants were divided into an HBO2 group and a placebo group while continuing their training routines. The HBO2 group was exposed to normal air for 15 minutes while the chamber was pressurized to 2.5 ATA, followed by three 25-minute sessions of 100% oxygen with five-minute air breaks between sessions. The placebo group was pressurized to 1.3 ATA and received 100% oxygen only during depressurization. Treatments were conducted twice a week for five weeks. Blood samples were taken before therapy began, after the fifth and tenth sessions, and two weeks post-treatment to assess creatine phosphokinase, myoglobin, lactate, blood urea nitrogen, and glutamic oxaloacetic transaminase.

Results revealed significant reductions in glutamic oxaloacetic transaminase, myoglobin, creatine phosphokinase, and pain in the HBO2 group after the fifth and tenth sessions. The HBO2 group also reported significant improvements in pain intensity and interference compared to the control group. These findings suggest that HBO2 is effective in reducing markers of muscle injury and alleviating pain, thereby supporting recovery.

Although multiple studies have concluded that HBO2 has no significant effect on DOMS (6), methodological issues such as small sample sizes, lack of randomization and blinding, and contradictory study designs limit their reliability (41). Further large-scale, randomized controlled trials are needed to obtain more definitive conclusions.

Ligament Injuries

Ishii et al. investigated the effects of HBO2 on ligament healing in the right hind limbs of 44 male Wistar rats with experimentally induced injuries (42). The rats were divided into four groups post-injury: (a) a control group that breathed room air in a hyperbaric chamber for 60 minutes; (b) HBO2 at 1.5 ATA for 30 minutes once a day; (c) HBO2 at 2 ATA for 30 minutes once a day; and (d) HBO2 at 2 ATA for

60 minutes once a day. Fourteen days after the injury, the researchers compared gross appearance, histology, and pro-alpha (I) mRNA expression across groups. HBO2 significantly enhanced ligament healing compared to the control group, with the most effective treatment being HBO2 at 2 ATA for 60 minutes daily, as evidenced by increased extracellular matrix deposition and collagen synthesis.

Horn et al. evaluated HBO2's effects on healing lacerated medial collateral ligaments (MCL) in 48 Sprague-Dawley rats (43). The right MCL was surgically lacerated, while the left remained intact as a control. Half of the rats underwent daily HBO2 at 2.8 ATA for 1.5 hours over five days. Stiffness and force to failure were assessed at 2, 4, 6, and 8 weeks post-surgery. At 4 weeks, the HBO2 group showed significantly increased force to failure in the injured ligaments compared to the control group, though no additional improvements were observed by 6 weeks.

Mashitori et al. studied 76 Sprague-Dawley rats with a 2-mm segment of the MCL removed (44). Thirty-eight rats received HBO2 at 2.5 ATA for 2 hours, five days a week, while the remaining rats were exposed to room air. The HBO2 group exhibited more scar tissue, significantly higher Type I procollagen gene expression at 7 and 14 days, and greater tensile strength and stiffness at 14 days. These findings indicate that HBO2 enhances scar tissue formation and improves ligament tensile properties.

In a double-blind, randomized, controlled study, Soolsma examined HBO2's effect on grade II MCL recovery in humans (45). The protocol included clinical assessments, MRI scans, and two weeks of either HBO2 (2 ATA, 100% oxygen, one hour daily) or sham treatment (1.2 ATA). Results showed that HBO2 reduced edema and muscle wasting, improved range of motion, and enhanced maximum knee flexion.

Takeyama et al. investigated the effects of HBO2 on medial collateral ligament (MCL) and anterior cruciate ligament (ACL) injuries in 64 Sprague-Dawley rats (46). HBO2-treated groups (2.5 ATA) displayed significantly higher Type I procollagen and TIMPs gene expression compared to controls. While HBO2 improved structural protein synthesis and inhibited degradation in ACL injuries, it was insufficient for complete healing. The authors suggested that HBO2 could enhance ACL surgery outcomes when used adjunctively.

Yeh et al. studied HBO2's effects on ACL reconstruction in rabbits (47). Forty rabbits were divided into an HBO2 group (2.5 ATA, 100% oxygen, 2 hours daily) and a control group. Postoperative analyses revealed that the HBO2 group exhibited increased Sharpey's fibers, enhanced neovascularization, and better tendon-bone integration. Biomechanical testing showed higher pullout strength, while electron microscopy revealed more compact collagen fibers in the HBO2 group.

HBO2 generally promotes ligament and tendon healing by enhancing scar tissue formation, collagen synthesis, and tensile strength. Its effectiveness is dose-dependent, with higher-pressure and longer-duration treatments yielding better results. However, some studies suggest benefits may plateau over time, highlighting the need for further research into optimal treatment protocols.

Bone Marrow Edema

Bone marrow edema is a common sports injury, particularly following acute trauma (48). If untreated, it can lead to complications such as osteonecrosis (49-51). Treatment options include pharmaceuticals like non-steroidal anti-inflammatory drugs (NSAIDs) and bisphosphonates, weight-bearing restrictions, and core decompression. However, these interventions may be less effective in cases of poor circulation (49,51,52).

HBO2 therapy offers additional benefits, including circulation improvement and anti-edema effects. It also promotes bone regeneration by enhancing osteosynthesis, neoangiogenesis, and vasculogenesis (18). Studies show that HBO2 stimulates the expression of osteogenic markers and increases mineral deposition in mesenchymal stem cells (53).

Clinical studies support the beneficial effects of HBO2 on osteonecrosis and bone marrow edema. Numerous reports document reduced pain scores, improved range of motion, enhanced quality of life, and radiographic improvements in patients with avascular necrosis of the femoral head following HBO2 therapy (54-60).

Moghamis et al. identified HBO2 as a promising, non-invasive alternative to core decompression for treating non-traumatic pre-collapse avascular necrosis of the femoral head (61). Additionally, Ververidis et al. reviewed eight studies (2004-2018) and found that HBO2 effectively resolved edema, relieved pain, and improved range of motion in patients unresponsive to conservative treatments. Although the time required for remission (15-90 sessions) was noted as a drawback, HBO2 was highlighted as a potential alternative for these cases (51).

CONCLUSION

This systematic review examines the potential benefits of HBO2 for various sports injuries. The literature is extensive, but standardization is challenging due to the diversity of injury types, the use of different animal models in experiments, the limited number of human studies, and the lack of randomization and blinding. Narrowing the scope of fu–

ture reviews to specific injury types could improve the practical value of such studies.

HBO2 appears more effective as an adjunctive treatment than a standalone therapy, with its impact varying by injury type. While no standardized treatment protocol has been established, evidence from existing studies suggests that a protocol involving 90 to 120 minutes of HBO2 at 2.0-2.5 ATA for at least five days a week could be optimal. The total number of sessions should be tailored to the patient's condition.

Future research should focus on standardizing treatment protocols, evaluating long-term effects, and conducting randomized, controlled, double-blind clinical trials with larger human sample sizes, particularly among athletes. This would enable more precise conclusions about the efficacy of HBO2 in sports injury management.

Despite some limitations, the literature provides encouraging evidence of HBO2's therapeutic potential for sports injuries. Continued research will help solidify its role as a valuable treatment modality.

Conflict of Interest / Çıkar Çatışması

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