Perspectives on Modern Orthopaedics

Hyperbaric Oxygen Therapy in Extremity Trauma

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Abstract

Hyperbaric oxygen therapy potentially can provide enhanced oxygen delivery to peripheral tissues affected by vascular disruption, cytogenic and vasogenic edema, and cellular hypoxia caused by extremity trauma. After appropriate resuscitation, macrovascular repair, and fracture fixation/stabilization, adjunctive hyperbaric oxygen therapy can enhance tissue oxygen content. In patients with crush injury or early compartment syndrome, hyperbaric oxygen therapy may reduce the penumbra of cells at risk for delayed necrosis and secondary ischemia. Animal experiments and human case series suggest the benefits of such therapy, and recent randomized, prospective studies on trauma patients have confirmed its efficacy in those with extremity trauma. However, more data are necessary to determine additional indications as well as optimal timing and dosing for hyperbaric oxygen therapy.

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Hyperbaric oxygen (HBO) therapy has been used as an adjunct to minimize secondary injury and enhance healing in patients with extremity trauma and other forms of acute traumatic peripheral ischemia. Both clinical and experimental evidence indicate that HBO therapy, used as an adjunct for management of extremity trauma, may improve outcome in select cases. However, more research is needed to adequately define which patients will benefit from HBO therapy. Appreciation of its potential applications in the management of extremity trauma requires an understanding of the therapy's mechanism of action and of its effects on various types of tissues.

Practical Considerations

HBO therapy allows patients to breathe 100% oxygen in a chamber under conditions of increased barometric pressure. It was first used in the late 1800s to treat caisson workers injured with decompression sickness (the "bends") during construction of the Hudson River tunnel in New York. Subsequently the military used it to treat the bends and air gas emboli. Beginning in the 1960s, animal experimentation and clinical case reports indicated applications for HBO therapy in the management of both severe anemia and gas gangrene.

There are more than 300 hyperbaric chambers in the United States, ranging from monoplace chambers 22 inches in diameter to large multiplace chambers able to accommodate more than 12 patients simultaneously in an intensive care setting. Most chambers in the United States are monoplace (Fig. 1). They are small (approximately 4 ft × 4 ft × 8 ft) and constructed of clear Plexiglas with metal end pieces. Individual patients lie on a gurney, the top surface of which slides into the chamber. Patients can see through the translucent chamber sides and communicate via an intercom system. Generally, high-flow oxygen fills the entire chamber so that the patient breathes the ambient gas without the need for a hood or mask breathing system. Patients are required to be supine for a 60- to 90-minute treatment period.

Advantages of the monoplace system include low initial cost of construction and ease of installation. In addition, no in-chamber attendant is needed. No published data indicate whether there is an advantage to the additional topical oxygen that results from treatment in a monoplace chamber. Disadvantages include lack of access to the patient, potential patient claustrophobia, limited depth of pressurization, and the increased fire hazard (because the entire chamber is filled with pressurized oxygen).

Multiplace chambers, generally found in major medical centers and teaching institutions, can accommodate from 2 to more than 12 patients (Fig. 2). Patients may be seated upright, sit semirecumbent in recliners, or lie supine on a gurney. The cham-

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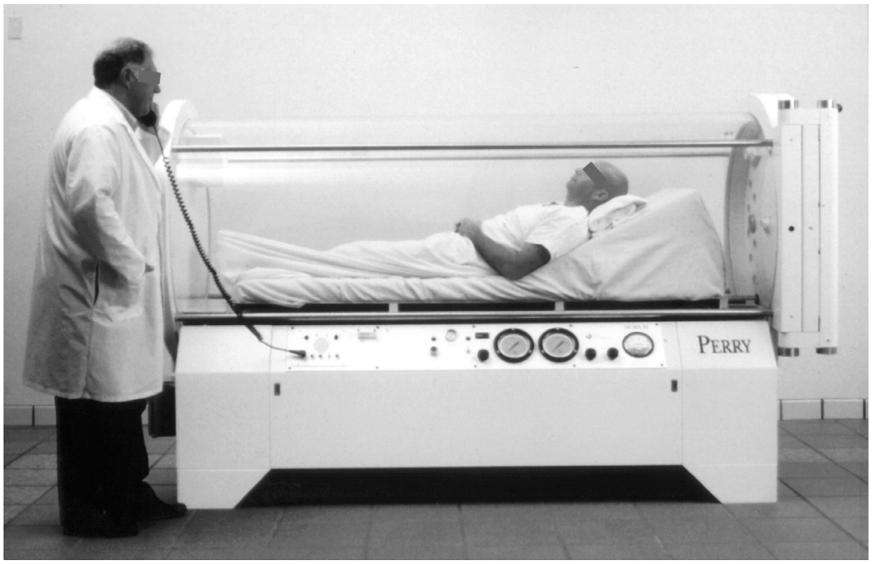
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Figure 1 Small monoplace hyperbaric oxygen chamber. (Courtesy of Perry Baromedical, Riviera Beach, FL.)

ber is pressurized with air, and patients breathe 100% oxygen through a hood or mask delivery system. Although it is possible to mechanically ventilate patients and render intensive care in a monoplace chamber,[1] direct patient access makes care of critically ill patients safer in a multiplace chamber. All patient treatments include an in-chamber attendant, who may be a physician, nurse, respiratory therapist, or hyperbaric technician. The attendant applies and removes the oxygen delivery hood or mask, checks vital signs, administers blood or medications as indicated, and monitors for signs of oxygen toxicity.

With the exception of patients with the bends, most HBO therapy treatments are administered at barometric pressures ranging from 1 to 2 atmospheres greater than the pressure experienced at sea level. To avoid confusion between terminology such as gauge pressure, feet of sea water, and absolute pressure, all pressures are designated as absolute atmospheres (ATA), which takes into account the ambient pressure at one atmosphere before the chamber is pressurized. Thus, most clinical hyperbaric medicine is practiced at 2 to 3 ATA—that is, 1 or 2 atmospheres greater than ambient pressure. Each atmosphere is considered to be 760 mm Hg; thus, a patient receiving 100% oxygen at 3 ATA is exposed to a pO_2 of 2,280 mm Hg (ie, 3 × 760 mm Hg). This tremendous partial pressure of oxygen supports gas diffusion for a much greater distance than under normal conditions, thus delivering oxygen to relatively ischemic and hypoxic tissues (Fig. 3).

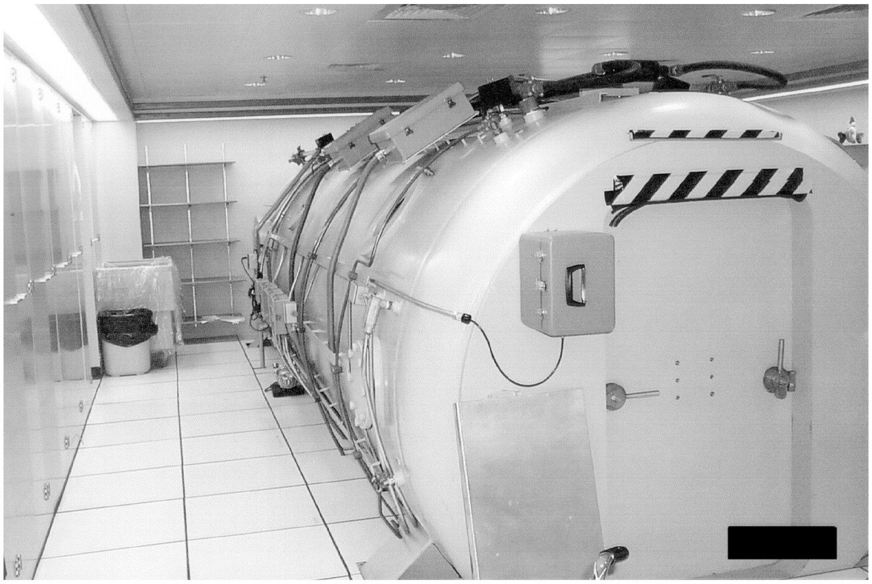
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Figure 2 Multiplace hyperbaric oxygen chamber capable of treating six patients simultaneously. (Courtesy of University of Iowa Health Care, Iowa City, IA.)

Indications and Contraindications

The 13 currently recognized indications for HBO therapy are listed in Table 1. All of these disease processes benefit from HBO therapy based on one or both of two phenomena: gas compression and solubility based on increased barometric pressure, or enhanced tissue oxygen delivery. Trauma-related indications for HBO therapy include carbon monoxide intoxication, gas gangrene, crush injury, compartment syndrome, necrotizing fasciitis, treatment of chronic osteomyelitis, support of grafts and flaps, and burns.

HBO therapy is an effective supplement to antibiotics and débridement of infected tissues. High leukocyte oxygen levels have been shown

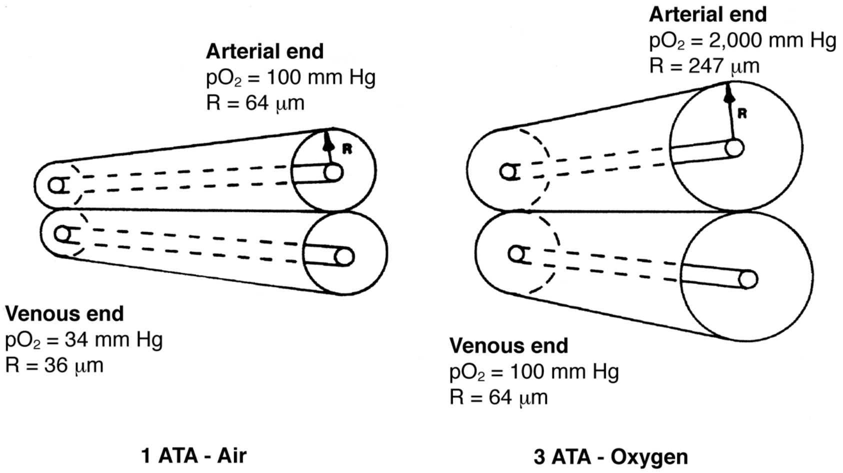

Figure 3 Theoretical oxygen diffusion cylinder radius under air-breathing conditions at 1 ATA (*left*) and under oxygen-breathing conditions at 3 ATA (*right*). Oxygen diffusion falls off with the square of the diffusion distance. Ultra-high levels of arteriolar O_2 can result in a greatly expanded volume of tissue that is above its anaerobic threshold. (Reprinted with permission from Sheffield PJ: Tissue oxygen measurements, in Davis JC, Hunt TK [eds]: *Problem Wounds: The Role of Oxygen.* New York, NY: Elsevier, 1988, p 38.)

to result in enhanced killing of pathogenic bacteria.[2,3] Elevation of tissue oxygen increased the so-called oxidative burst that ultimately dispatches ingested pathogens. Many wounded and/or infected tissues are suboptimally supplied with oxygen for clearing an infection. The Km (concentration yielding half-maximal activity) for oxygen-dependent bacterial killing is 45 to 80 mm Hg.[3]

The function of many conventional antibiotics is dependent on ambient oxygen levels. Increases in ambient oxygen are thought to enhance both antibiotic uptake and effectiveness.[4] The duration of the postantibiotic effect of tobramycin against *Pseudomonas aeruginosa* was nearly doubled by exposure to 2.8 ATA of HBO therapy. Aminoglycosides are taken up into bacteria by an oxygen-dependent active pump.

Contraindications relate to issues of gas exchange, oxygen sensitivity, and technical safety (Table 2). Any gas-filled space in the body will be compressed by the external application of pressure in the HBO chamber, so there must be a means of pressure equilibration. The two locations in which this is most problematic are the middle ear and the chest cavity.

Patients must be able to equilibrate the pressures on either side of the tympanic membrane—similar to equilibrating pressures when diving to the bottom of a pool or when changing altitude in an airplane. Pinching the nose and performing a Valsalva maneuver or swallowing may help the conscious patient open the proximal aspect of the eustachian canal and allow pressure on the medial aspect of the tympanic membrane to match the pressure outside the ear. Approximately 1% to 4% of patients are unable to clear their ears despite expert coaching and will require tympanostomy and myringotomy tubes or risk traumatic rupture of the eardrum.[5] Because intubated patients are unable to close the glottal opening and perform a Valsalva maneuver, they are routinely administered a bilateral myringotomy and ear tube placement.

The volume of an undrained pneumothorax diminishes in size as the patient is compressed in the HBO chamber. However, if any further air is added to the pneumothorax when the patient is at depth, the bubble will increase greatly in size as the patient is decompressed at the end of the treatment; a tension pneumothorax may result. Thus, all pneumothoraces must be drained before HBO therapy, and physicians who administer HBO therapy should be competent to perform needle thoracostomy in case a pneumothorax develops while the patient is in the HBO chamber. Therefore, neither a pneumothorax nor a bronchopleural fistula is a contraindication to HBO therapy once a functioning thoracostomy tube has been placed. Patients with difficulties in gas exchange, such as those with severe chronic obstructive pulmonary disease or active status asthmaticus, are at risk for inability to equilibrate gas pressures along the tracheobronchial tree and are considered to be at increased risk for HBO therapy.

Table 1
Indications for Hyperbaric Oxygen Therapy

- Air or gas embolism
- Carbon monoxide poisoning
- Clostridial myositis and myonecrosis (gas gangrene)
- Crush injury, compartment syndrome, or acute traumatic peripheral ischemia
- Decompression sickness
- Enhancement of healing in select problem wounds
- Exceptional blood loss anemia
- Intracranial abscess
- Necrotizing soft-tissue infections
- Osteomyelitis (refractory)
- Delayed radiation injury (soft-tissue and bony necrosis)
- Skin flaps and grafts (compromised)
- Thermal burns

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Table 2
Contraindications to Hyperbaric Oxygen Therapy

Absolute	Relative
Bleomycin exposure	Severe chronic obstructive pulmonary disease/asthma
Undrained pneumothorax	Seizure disorder
Concurrent chemotherapy/radiation therapy	Severe claustrophobia
Pressure-sensitive implanted medical device (eg, automatic implantable cardiac defibrillator, pacemaker, dorsal column stimulator, insulin pump)	Chronic sinusitis/upper respiratory infection
Patient refusal	History of spontaneous pneumothorax
	High fever/dehydration

Reprinted with permission from Kindwall EP: Contraindications and side effects to hyperbaric oxygen treatment, in Kindwall EP, Whelan HT (eds): *Hyperbaric Medicine Practice*, ed 2. Flagstaff, AZ: Best Publishing Company, 1999.

Oxygen sensitivity is another contraindication in HBO exposure.[6] Several chemotherapeutic agents, such as cyclophosphamide and the anthracyclines (doxorubicin, daunorubicin, and idarubicin) exert their tumoricidal effects through generation of oxygen free radicals. The toxicity of these drugs is exacerbated by high oxygen exposure; therefore, concomitant administration of these drugs and HBO is contraindicated. Bleomycin, a chemotherapeutic agent used for germ cell tumors, is unique in that it may pose a lifelong risk of oxygen toxicity (although this is controversial[7,8]). Thus, prior exposure to bleomycin, historically used to treat testicular cancer, is a strong relative contraindication to HBO therapy.

Complications and Toxicity

Oxygen toxicity has two major manifestations: in the central nervous system (CNS) and in the respiratory system. The course of oxygen-induced seizures in the CNS is not known. Disruption of gamma-aminobutyric acid metabolism in the brain may occur with loss of tonic inhibitory nerve traffic; this remains an area of active investigation.[5] Sensitivity to oxygen-induced seizures seems to vary, both between individuals and within an individual under varying conditions. Because seizure is universal at 3 ATA with unremitting oxygen exposure >4 hours, 100% oxygen is not administered at depths >3 ATA. To minimize the risk of seizure, patients should be well hydrated and given periods of air breathing (air breaks) while in the HBO chamber. With these precautions, the reported seizure incidence is 1.3: 10,000 treatments at the standard wound treatment depth of 2.4 ATA.[5] Therapy for oxygen-induced seizures consists of removing the patient from high oxygen exposure. In the multiplace chamber, removal of the hood or breathing mask is sufficient; the seizure will quickly resolve without further therapy. There are no known long-term sequelae to a properly managed oxygen-induced seizure.

Pulmonary oxygen toxicity is rarely a concern because it requires longer exposure to high oxygen levels than CNS toxicity limits would allow. There may be a risk of pulmonary oxygen toxicity in patients who go from high oxygen exposure in an intensive care unit (ICU) setting to the HBO chamber, then back to high oxygen exposure in the ICU (ie, where there is unremitting high oxygen exposure).[9] Vitamin E has been used as an antioxidant, with anecdotal resolution of pulmonary symptoms in patients for whom the benefit of high oxygen exceeds the risks (eg, a Jehovah's Witness patient with a hematocrit level <5%).[9,10]

Claustrophobia ranges in incidence from 10% in the monoplace chamber to 2% in the multiplace facility.[5] Generally, reassurance and mild sedation with benzodiazepines are sufficient to help the patient complete treatment. Occasionally, consenting but anxious patients require sedation or anesthesia to complete the treatment course, similar to some MRI procedures.

Fire is the most catastrophic event that can befall a hyperbaric chamber. The major components of a fire triangle are oxygen, fuel, and an energy source. Because the oxygen level is elevated, efforts to minimize the other two components of the fire triangle must be unrelenting. Combustible materials inside the chamber are kept to a bare minimum. There is no AC power source inside modern HBO chambers. Lights are located outside the pressure hull, and light is transmitted into the chamber via fiberoptic wands. Communication headsets and patient monitors are low-voltage DC devices. Patients and in-chamber attendants wear all cotton scrubs or gowns to minimize the chances of a friction-induced spark. Patients are instructed to avoid petroleum-based cosmetics and hair products. All patients are inspected to detect possession of incendiary materials, such as matches or lighters. The oxygen concentration in the multiplace chamber is carefully monitored to ensure that the fraction of inspired air (FIO_2) remains below 24%. Only the hood or mask worn by the patient contains 100% oxygen. All gas exhaled by the patient is scavenged and dumped outside the chamber to avoid oxygen build-up. Finally, elaborate fire suppression systems are required on all multiplace chambers to immediately quench any flame.

Mechanisms of Action

The amount of gas dissolved in a liquid is proportional to the pressure of the gas over the liquid. Arterial blood pO_2 values >1,500 mm Hg are obtained when patients breathe 100% oxygen at 3 ATA. This supraphysiologic pO_2 increases plasma oxygen content to the point at which cellular metabolism can be supported by blood nearly devoid of erythrocytes.[9,11] More importantly, these high pO_2 values allow for a greatly expanded radius of diffusion for oxygen (Fig. 3). There is a steep gradient of pO_2 from open capillaries to the edge of a wound. Large increases in pO_2 push the zone of hypoxia outward from a capillary closer to a wound edge.[12] As a result, tissues with borderline ischemia or hypoxia can be intermittently supplied with oxygen in quantities sufficient to accelerate wound healing, enhance leukocyte microbiocidal function, and stave off necrosis. Depending on several variables (eg, tissue metabolic rate), oxygen levels can remain elevated for 1 to 3 hours after an HBO treatment period.[13]

Acute Traumatic Peripheral Ischemia

HBO therapy may benefit patients with extremity trauma in different phases of the recovery process. Acute traumatic peripheral ischemia involves a primary injury from direct energy transfer to tissue. A gradient of injury extends out from the center of the force or impact. Tissues at the point of impact may be nonviable regardless of intervention. The next zone outward consists of variably injured tissues that may recover with appropriate intervention. Most therapeutic maneuvers are focused on this penumbra of tissue in an attempt to maximize recovery of the injured but viable tissue. Finally, an outer zone of noninjured or minimally injured tissues that are not subject to primary injury may be at risk from the processes of secondary injury resulting from delayed, physiologic responses to injury. The quantity of tissue loss and destruction caused by secondary injury can dwarf the actual loss from the primary traumatic event. For example, a high-velocity projectile penetrating the lower leg creates a zone of primary tissue destruction in the missile path. All tissue contacted by the missile will be dead and, therefore, beyond salvage. Outward from the missile path is a zone of blast injury that extends radially as a cylinder from the missile track. Even without macrovascular disruption, there is disruption of microvascular arcades. Delicate vascular supply networks are disrupted in the bullet path and beyond. As disrupted vessels undergo vasospasm, blood flow stasis, and retrograde thrombosis, the zone of effective ischemia and hypoxia moves outward from the track of primary injury.

Injured but viable cells in the penumbra have increased oxygen needs at the very time when oxygen delivery is decreased by disruption of the microvascular supply.[14] Both cytogenic and vasogenic edema result in increases in interstitial pressures. These pressures can exceed venous hydrostatic pressure, with resultant venous stasis. Retarded venous outflow, along with continued arterial inflow, causes further fluid transudation at the capillary level. Even vessels that are not disrupted may have their permeability characteristics altered by histamine and other factors released by nociception, hypoxia, and ischemia.[15] The result is a feed-forward cycle of ischemia, cellular hypoxia, edema formation, and further ischemia. As a result of this secondary injury process, tissues completely remote and otherwise unaffected by the primary injury are at risk of necrosis and death. Compartment syndrome is the classic example of this pathologic process of secondary injury.

HBO therapy is applied to reverse or mitigate the process of secondary injury in extremity trauma and to minimize resultant tissue loss at different points in the pathologic and recovery processes. Taken sequentially, these processes include secondary injury and healing stage complications, such as flap and graft preservation and adjunctive therapy for soft-tissue and bony infection.

Treatment Effect

HBO therapy minimizes secondary injury in crush and compartment syndromes by at least four mechanisms. First, with enhanced oxygen delivery, arterial oxygen tensions of 800 to 1,500 mm Hg provide an enhanced gradient for diffusion, thereby increasing effective diffusion volume up to sixteenfold. Second, by reducing tissue edema, the high oxygen concentration acts as a direct vascular smooth-muscle contractile stimulus, thus causing arteriolar vasoconstriction. This effect would seem to be undesirable in the face of relative ischemia, but the high oxygen content of the blood more than compensates for any reduction in blood flow. Simultaneously, because of increases in upstream arterial resistance, capillary hydrostatic pressures are reduced, thereby favoring resorption rather than formation of tissue edema. Third, leukocyte function is enhanced. Polymorphonuclear leukocyte function generates an oxidative burst, which is lethal to ingested bacteria. This is a substrate-limited process; oxygen is the limiting substrate at both physiologic and pathologic oxygen levels.[2,3] Finally, there is quenching of oxygen free radicals and mitigation of biochemical processes underlying the so-called no-reflow phenomenon. Despite restoration of macrovascular integrity, much of the damage in secondary injury is caused by a failure of microvascular flow.

Even when major vascular structures are opened, a failure of flow and substrate delivery at the microvascular level can be demonstrated, referred to as ischemia reperfusion injury. This is an important phenomenon for the fields of trauma, transplant, graft, and vascular surgery as well as clinical cardiology and neurology. The physicochemical causes of ischemia reperfusion injury are under investigation.[15] When microvascular flow is disrupted, a cascade of biochemical changes occurs, such as alterations in endothelial oxidase enzymes, modification of endothelial adhesion molecules, stasis and activation of neutrophils, and generation of oxygen free radicals.[16] Leukocyte-endothelial adhesion and polymorphonuclear leukocyte–related generation of damaging lipid peroxidation products are central to ischemia reperfusion injury. Although seemingly counterintuitive, ultra-high levels of oxygen can quench the production of peroxidation molecules and interrupt many of the metabolic cascades that may cause ischemia reperfusion injury. Thom and Elbuken[17] demonstrated that hyperoxia-altered free radical formation in vitro favored formation of protective hydroperoxyl radicals. These latter compounds react with lipid radicals in a quenching reaction that terminates the chain reaction of lipid peroxidation.[17,18]

Results

Basic Research

In a rat model, a standardized crush injury was applied for 2 hours to a hindlimb.[19] After the injury, one group was treated with mannitol (1 g intravenous), one with HBO (three treatment sessions of 90 minutes' duration each at 2.5 ATA), and one with both therapies; there was one control group. At 1 week after injury, the animals were again anesthetized, and the response of the injured muscle to direct muscle stimulation or to stimulation of the intact motor nerve was recorded and expressed as a percentage of the response of the noninjured hindlimb. All three treatment arms (HBO, mannitol, HBO and mannitol) appeared to preserve direct muscle responses better than did the control group. The combination of mannitol and HBO showed better preservation of nerve and muscle function than was shown in the untreated control group or mannitol-alone group. Even though the combination of mannitol and HBO yielded the best neuromuscular recovery (after experimental crush syndrome), rats treated with HBO alone fared worse than did the other experimental groups. This paradox requires further study.

Both mannitol and HBO act to reduce interstitial edema but through different mechanisms. Mannitol may serve as a colloid that reduces excess fluid in damaged nerve or muscle cells. Mannitol is also known to scavenge peroxidation products that may result when vascular occlusion is released.[20] Oxygen is a direct-acting vasoconstrictor.[21,22] HBO treatment causes a 10% to 20% increase in systemic vascular resistance. This arteriolar vasoconstriction causes a lower downstream capillary hydrostatic pressure and alters the balance of Starling forces to favor interstitial fluid resorption. Also, high oxygen content in any plasma streaming past areas of near-total occlusion may be sufficient to maintain cellular ion gradients and prevent the cytogenic edema that accompanies a reduction in cellular energy charge. One study indicated a 50% reduction in postischemic edema formation in a rat tourniquet model with only one or two HBO treatments.[23] Reduction in edema formation results in less external compression of capillaries and venules. It also causes a reduction in the intercapillary spacing that determines the size of the cylinder of parenchymal tissue that must be supplied by an open capillary.

In a study of compartment syndrome in dogs, Strauss et al[24] induced compartment pressures of 100 mm Hg in the anterior compartment of the hindlimb through infusions of autologous plasma. These pressures of 100 mm Hg were maintained for 8 hours and measured continuously using wick or slit catheters. Two hours after completing the 8 hours of compartmental pressurization, the dogs were treated with HBO for 1 hour at 2 ATA while breathing 100% oxygen. The animals received two additional HBO treatments of 1 hour each over the next 10 hours. Two days after the compartment syndrome was induced, the animals were injected with technetium Tc 99m to quantify muscle necrosis and then were sacrificed. There was a significant ($P < 0.05$) reduction in both edema and muscle necrosis in the experimentally pressurized leg compartment when HBO was instituted. It is not known whether this tissue protection is caused by plasma-dissolved oxygen streaming through vessels that no longer have flowing cellular elements or by a quenching of peroxidation reactions in the postocclusive state.[18]

Clinical Studies

Most clinical reports on HBO efficacy in extremity trauma are observational. A report from a battlefield setting described seven soldiers who continued to exhibit signs and symptoms of peripheral ischemia despite successful macrovascular repair. Intermittent HBO therapy instituted for 2-hour treatments at 2.8 ATA was instrumental in preventing amputation in all seven patients when gangrene had been deemed imminent by the surgeon before starting HBO.[25]

Shupak et al[26] reported on 13 patients with lower extremity trauma complicated by vascular injury, peripheral neurologic injury, and extensive soft-tissue damage. Most had both arterial and venous disruption; after vascular repair, patients with continued evidence of ischemia (despite macrovascular continuity) were treated with HBO at 2.4 ATA for 90 minutes per treatment for an average of five treatments (range, two to eight). Complete limb salvage was achieved in eight patients (62%). The line of amputation was moved distally in four (31%), and only one patient (7%) failed to show improvement with HBO therapy. The authors concluded that if evidence of ischemia persists after macrovascular integrity has been reestablished, HBO therapy should be instituted immediately.

In 1996, Bouachour et al[27] performed the first randomized, double-blind, placebo-controlled human trial of HBO as part of crush injury management. Of 36 patients with crush injuries, 18 were randomized to HBO at 2.5 ATA two times per day for 6 days. The 18 who served as control patients breathed air at 1.1 ATA on the same schedule. Patient demographics and comorbid disease states were comparable. Fracture severity and soft-tissue wounds were similar in the two groups. Complete wound healing without tissue necrosis occurred in 17 of 18 HBO patients (94%) and in 10 of 18 control patients (56%) ($P < 0.01$). None of the 18 patients treated with HBO therapy required amputation, but 2 of the 18 control patients did. Placebo-treated patients experienced a greater need for repetitive surgical procedures compared with the HBO group ($P < 0.05$). Perhaps most importantly, transcutaneous oxygen values and the response of these values to HBO therapy served as good discriminators for wounds that healed completely versus those that progressed to tissue necrosis. In patients with complete healing, transcutaneous oxygen values on room air rose from 21.6 ± 5.7 mm Hg to 90 ± 20 mm Hg over a series of 12 HBO treatments, which was a significant ($P < 0.001$) increase in tissue oxygenation. No significant increase in transcutaneous oxygen occurred after 12 sham treatments. This study demonstrated both the efficacy of HBO therapy and the importance of transcutaneous oxygen values as an objective predictor for wound healing or failure during HBO support.

Evidence for the efficacy of HBO in compartment syndrome exists only in the form of case series and case reports. In 1989, Strauss and Hart[28] reported on 10 patients referred for HBO therapy when their compartment pressure measurements were elevated but before surgical intervention was indicated. No criteria required for surgery were specified. Symptoms of pain, swelling, and paresthesia already were present, and compartment pressures ranged from 15 to 48 mm Hg. These patients were treated with HBO therapy at 2 ATA for 90 minutes two or three times a day; all recovered completely without recourse to surgical intervention. In these cases of early elevated compartment pressures, HBO treatment appears to have truncated the expected pathologic progression of the syndrome and obviated the need for surgery. A second group of 10 patients underwent fasciotomy, but HBO treatment was requested after the operation to help with wound healing, demarcation of viable and nonviable tissue, and resolution of peripheral nerve palsy. Although not in a controlled trial, these patients were thought to have more rapid resolution of their edema, faster wound closure, reduced tissue loss to débridement, and better resolution of peripheral neuropathy than would have been anticipated given their clinical presentation.[28]

Although there are no randomized, prospective, controlled human trials of HBO therapy, case series appear to indicate efficacy, particularly when the therapy is instituted early in the developing course of the syndrome. No intervention has been shown to interrupt the pathologic progression of compartment syndrome. The standard of care has been repeated examination and repeated compartment pressure readings to discern which patients would resolve spontaneously and which would require fasciotomy. Now it may be possible to alter the natural progression of this pathologic process. The current treatment of established compartment syndrome is emergent fasciotomy. However, when this procedure reveals at-risk muscle, there may be a role for HBO therapy after surgery. These modest levels of proof, in conjunction with Bouachour's findings in crush injury,[27] indicate the need for a trial of HBO therapy for elevated compartment pressures before development of an established clinical compartment syndrome and after surgical release, when the presence of viable muscle and other tissue is marginal.

Current Standards for Clinical Use

HBO therapy may be used in a variety of clinical scenarios in which there is marginally viable tissue, including true crush syndromes and certain high-grade open fractures, most commonly tibial fractures. HBO treatments are initiated at 2.4 ATA for 90 minutes with 100% oxygen as soon as macrovascular integrity has been established. Clinical evidence of tissue viability can be supplemented with transcutaneous oxygen data from areas at or distal to the site of crush. Typically 10 to 12 daily treatments may be required. These treatments are performed concurrently with active wound management, débridement, tissue coverage, and use of antibiotics.[27]

Established compartment syndrome should be managed with emergent fasciotomy. Patients in whom compartment pressures or clinical examination are borderline can be treated with HBO therapy twice daily with the same treatment parameters as those for crush injury; however, patients generally respond with 1 to 2 days of twice-daily treatment. Repeated or continuous compartment pressure measurements supplement clinical symptomatology in assessing whether the compartment syndrome is progressing or resolving.[29,30] Patients whose compartment syndrome progresses despite prompt HBO treatment should undergo urgent surgical release of the affected compartments. HBO therapy also has been used in patients after release of established compartment syndrome when clinical examination indicates that there is marginally vascularized muscle.

Cost

HBO chambers range in cost from \$150,000 for a used monoplace chamber to several million dollars for an elaborate multiplace chamber system. Typical charges for HBO therapy range from \$500 to \$1,000 per session, which is reimbursed by most insurance carriers for any of the 13 medical indications listed in Table 1.

Cost effectiveness estimates depend on multiple variables, such as the indication treated and relative costs of other therapies. Although hard data are difficult to obtain, some estimates indicate that HBO treatments can be cost effective. Strauss[31] examined cost issues related to complicated fractures and reported that the additional cost of HBO is more than compensated for by the reduction in overall medical costs, particularly for severe limb injuries with a marginally vascularized wound bed from crush and/or compartment syndrome. A 20-treatment HBO series to salvage a limb with a nonhealing diabetic foot wound cost \$12,000 to \$20,000; the immediate cost of a below-knee amputation exceeds \$25,000, with estimates of ongoing economic impact exceeding thousands of dollars per year.[31]

Summary

Controlled animal experiments and human case series suggest that use of adjunctive HBO therapy for various forms of acute traumatic peripheral ischemia caused by extremity trauma is efficacious. Appropriate application of HBO therapy may minimize functional losses in patients with crush injury and compartment syndrome. Use of HBO is an expensive, technologically intensive therapy that should be reserved for instances in which there is evidence of efficacy and cost effectiveness. Because all limb injuries have some extent of microvascular insult and tissue necrosis, judgment is required to determine which patients may benefit from this complex therapy. Further basic and clinical studies are required to delineate optimal indications, timing, and dosing protocols for HBO therapy in extremity trauma. Transcutaneous oxygen measurements show promise as predictors of which patients will benefit from this unique treatment modality.

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