Oxidative stress is fundamental to hyperbaric oxygen therapy

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**Abstract:** The goal of this review is to outline advances addressing the role that reactive species of oxygen and nitrogen play in therapeutic mechanisms of hyperbaric oxygen. The review will be organized around major categories of problems or processes where controlled clinical trials have demonstrated clinical efficacy for hyperbaric oxygen therapy. Reactive species are now recognized to play a major role in cell signal transduction cascades, and the discussion will focus on how hyperbaric oxygen acts through these pathways to mediate wound healing and ameliorate post-ischemic and inflammatory injuries.

**Introduction:** Therapeutic mechanisms of action for hyperbaric oxygen (HBO₂) are based on elevation of both the partial pressure of oxygen and hydrostatic pressure. Elevating the hydrostatic pressure increases partial pressure of gases and causes a reduction in the volume of gas-filled spaces according to Boyle’s law. These actions have direct relevance to treating pathological conditions in which gas bubbles are present in the body, such as arterial gas embolism and decompression sickness. The majority of patients who undergo HBO₂ therapy are not treated for bubble-induced injuries hence therapeutic mechanisms are related to an elevated O₂ partial pressure. A summary of these mechanisms is shown in Figure 1.

It is well accepted that reactive oxygen species (ROS) mediate O₂ toxicity, which for HBO₂ encompasses pulmonary injuries, central nervous system effects manifested by grand mal seizures, and ocular effects such as reversible myopia (29). ROS and reactive nitrogen species (RNS) also serve as signaling molecules in transduction cascades, or pathways, for a variety of growth factors, cytokines and hormones (6, 25, 82, 123). As such, reactive species can generate either ‘positive’ or ‘negative’ effects depending on their concentration and intracellular localization. While more is still to be learned about the role ROS and RNS play in therapeutic responses of HBO₂, this review will take stock of how far the field has progressed. The review will be organized around major categories of problems or processes where controlled clinical trials have demonstrated clinical efficacy for HBO₂.
ROS are generated as natural by-products of metabolism and they include superoxide (O$_2^-$), hydrogen peroxide (H$_2$O$_2$), hypochlorous acid (HClO) and hydroxyl (•OH). ROS are increased in many organs by hyperoxia (60). Scavenging antioxidants combat the overproduction of reactive species. Enzymatic antioxidants include superoxide dismutase, catalase, thioredoxin- and glutathione-dependent peroxidase(s) and reductase(s). Acting in conjunction with these enzymes are the non-enzymatic antioxidants vitamin C, vitamin E, thioredoxin, glutathione, uric acid, β-carotene and carotene (124). Because exposure to hyperoxia in clinical HBO$_2$ protocols is rather brief (typically ~2 hours/day), studies show that antioxidant defenses are adequate so that biochemical stresses related to increases in ROS are reversible (33, 34, 89, 97).

RNS include nitric oxide (NO) and agents generated by reactions between NO, or its oxidation products, and ROS. There are three nitric oxide synthase enzymes responsible for synthesizing NO while converting L-arginine to L-citrulline; NOS-1 (neuronal NO synthase, nNOS), NOS-2 (inducible/inflammatory NO synthase, iNOS) and NOS-3 (endothelial NO synthase, eNOS). Peroxynitrite (ONOO-) is the product of a reaction between O$_2^-$ and NO (10). Additionally, peroxide enzymes, and especially myeloperoxidase, can catalyze reactions between nitrite (NO$_2$), a major oxidation product of NO, and hydrogen peroxide or hypochlorous acid to generate oxidants such as nitryl chloride and nitrogen dioxide that are capable of nitration and S-nitrosylation reactions (18, 72, 99).

**Wound healing:** HBO$_2$ is used in current practice to treat refractory diabetic wounds and delayed radiation injuries. A typical treatment protocol is daily exposures to 2.0 to 2.4 atmospheres absolute (ATA) for 90 to 120 minutes for 20 to 40 days. Treatments often include so-called air breaks, where a patient breathes just air for 5 minutes once or twice through the course of a treatment. This intervention has been demonstrated to enhance pulmonary O$_2$ tolerance (52).
Discussion of the pathophysiology of diabetic wounds and delayed radiation injuries is beyond the scope of this review, and the reader is referred to several recent publications (32, 42). Common elements shared by both disorders include depletion of epithelial and stromal cells, chronic inflammation, fibrosis, an imbalance or abnormalities in extracellular matrix components and remodeling processes, and impaired keratinocyte functions (17, 32, 42, 79, 109, 121). Diabetic wound healing is also impaired by deceased growth factor production, while in post-radiation tissues there appears to be an imbalance between factors mediating fibrosis versus normal tissue healing (17, 32, 121).

The effectiveness of HBO₂ as an adjuvant therapy for the treatment of diabetic lower extremity ulcerations is supported by six randomized trials and evaluations from a number of independent evidence-based reviews (1, 2, 49, 53, 69). The pathophysiology of radiation injury is obviously different than diabetic wounds, but the varied tissue abnormalities have been likened to a chronic wound (32). The benefit of HBO₂ for radiation injury also has been shown in randomized trials and its utilization supported by independent evidence-based reviews (11, 30, 81). It is important to state that for both diabetic wounds and radiation injuries, HBO₂ is used in conjunction with standard surgical management techniques. That was the format followed in clinical trials demonstrating its efficacy. By itself, or if used only in a post-operative period, HBO₂ is frequently inadequate treatment (7, 76). Animal trials have also documented benefits of HBO₂ (45, 46, 80, 138). The basis for its efficacy is only partially understood, but appears to be a combination of systemic events as well as local alterations within the wound margin (see Fig. 1).

Neovascularization occurs by two processes. Regional angiogenic stimuli influence the efficiency of new blood vessel growth by local endothelial cells (termed angiogenesis) and they stimulate the
recruitment and differentiation of circulating stem/progenitor cells (SPCs) to form vessels de novo in a process termed vasculogenesis (27, 51, 112). Clinical HBO₂ has effects on both these processes.

HBO₂ reduces circulating levels of pro-inflammatory cytokines under stress conditions [e.g. endotoxin challenge (43)] and in wounded tissues or isolated cells HBO₂ increases synthesis of many growth factors. HBO₂ does not alter circulating levels of insulin, insulin-like growth factors, or pro-inflammatory cytokines [e.g. tumor necrosis factor (TNF)-α, interleukin (IL)-6 and IL-8] in normal healthy humans (28, 43). Vascular endothelial growth factor (VEGF) and angiopoietin, as well as stromal derived factor-1 (SDF-1) influence SPCs homing to wounds and SPCs differentiation to endothelial cells (55, 92). Synthesis of VEGF has been shown to be increased in wounds by HBO₂, and it is the most specific growth factor for neovascularization (107). HBO₂ also stimulates synthesis of basic fibroblast growth factor and transforming growth factor β1 by human dermal fibroblasts (64), angiopoietin-2 by human umbilical vein endothelial cells (74), and it up-regulates platelet derived growth factor (PDGF) receptor in wounds (14). Extracellular matrix formation is closely linked to neovascularization and it is another O₂-dependent process (57). Enhanced collagen synthesis and cross-linking by HBO₂ have been described, but whether changes are linked to the O₂-dependence of fibroblast hydroxylases, which have a Kₘ for O₂ of ~25 mmHg, well below that achieved in the presence of HBO₂ versus some alteration in balance of wound growth factors, metalloproteinases and inhibitors of metalloproteases, is as yet unclear (36, 57, 135).

Oxidative stress at sites of neovascularization will stimulate growth factor synthesis by augmenting synthesis and stabilizing hypoxia inducible factor (HIF)-1 (58, 87). Hypoxia inducible transcription factors are heterodimers of HIF-α and a constitutively expressed HIF-β (also called the aryl hydrocarbon receptor nuclear translocator [ARNT] subunit). Enhanced growth factor synthesis by HBO₂ is due at least in part to augmented synthesis and stabilization of HIFs (107, 115, 116). While
this clearly sounds paradoxical, even under normoxic conditions HIF activity is regulated by a variety of cellular micro-environmental modifications. It is well recognized that expression and activation of HIF-α subunits are tightly regulated, and their degradation by the ubiquitin-proteasome pathway typically occurs when cells are replete with O₂ (98, 103). However, whether hypoxic or normoxic conditions prevail, free radicals are required for HIF expression (16, 39, 100, 102, 103). In addition to ROS, synthesis of NO is required for VEGF-mediated angiogenesis (44), and many down-stream effects of VEGF are stimulated via NO (8, 91).

There are three distinct HIF-α proteins: HIF-1α, 2α, and 3α. HIF-1 and 2 coordinate many cell responses involved with neovascularization by regulating gene transcription and, while there is substantial overlap in their activity, there are also a number of genes preferentially regulated by either HIF-1 or -2 (126). The biological function of HIF-3 is unclear, and at least one splice variant negatively modulates HIF-1α and -2α, although its expression is restricted to specific tissues and subject to hypoxic conditions (77, 83).

The influence HBO₂ has on HIF isoform expression appears to be conflicting and further work is needed to elucidate what are likely to be variations based on tissue-specific responses. Additionally, higher or lower levels of HIF isoforms may vary based on chronology [e.g. looking early or late after wounding or an ischemic insult]. One recent model showing accelerated wound healing by HBO₂ reported lower HIF-1 levels at wound margins, along with reduced inflammation and fewer apoptotic cells (138). In contrast, higher levels of HIF-1 have been linked to elevated VEGF in wounds in response to hyperoxia (58, 107). Recently, exposure to HBO₂ was shown to elevate HIF-1 and -2 levels in vasculogenic SPCs. The basis for this effect is augmented production of the antioxidant, thioredoxin and one of its regulatory enzymes, thioredoxin reductase, in response to oxidative stress (115). Among other actions, thioredoxin has been shown to promote the expression and activity of
HIFs (40, 62, 130). HIF-1 and -2 then secondarily can stimulate transcription of many genes involved with neovascularization including SDF-1 and its counterpart ligand, CXCR4, as well as VEGF. A physiological oxidative stress that triggers the same pathway is lactate metabolism (87).

Bone marrow NOS-3 activity is required for SPCs mobilization (4). SPCs mobilization is compromised by diabetes, apparently because NOS activity can be impaired due to responses related to hyperglycemia and a reduced presence of insulin (13, 22, 37, 38). In addition, radiation and chemotherapy, along with other factors such as age, female gender and coronary artery disease, are known to diminish SPCs mobilization (59, 94, 101, 125). By stimulating NO synthesis in bone marrow, HBO2 mobilizes SPCs in normal humans and patients previously exposed to radiation (118) and preliminary observations suggest the same is true for diabetic patients (116, 133). In animal models SPCs mobilized by HBO2 home to wounds and accelerate healing (45, 46, 115). HBO2 also improves clonal cell growth of SPCs from humans and animals (118). Functional enhancements of SPCs by HBO2 appear to be related to augmentation of HIF-1 and -2 levels (115).

Therefore, to summarize, HBO2 can stimulate healing in refractory wounds and irradiated tissues. One oxidative stress response that triggers improved function, at least for SPCs, involves elevations of thioredoxin and thioredoxin reductase which secondarily increase HIF-1 and HIF-2. The influence of HBO2 on HIFs in other cell types or tissues is variable. Increased synthesis of growth factors and collagen has been demonstrated. A separate free radical-based mechanism for augmentation of neovascularization by HBO2 is bone marrow SPCs mobilization, which increases the number of circulating SPCs that may home to injured tissues.

Reperfusion/inflammatory injuries and HBO2: For this review, we will group a variety of disorders together to facilitate the discussion on mechanisms of HBO2, although we admit this approach grossly simplifies complex pathophysiological processes. Clinical HBO2 protocols for these conditions are
much shorter than for wound healing. Treatments occur for just a few days rather than weeks; they are performed at higher O₂ partial pressures (~2.5 to 3.0 ATA) and may occur multiple times in the same day.

Skin graft and flap failures may be due to ischemia-reperfusion injuries. A prospective, blinded clinical trial found that administration of HBO₂ prior to and for three days following the procedure led to a significant 29% improvement in graft survival (93). This is the only randomized clinical trial on skin grafts, but numerous animal studies support its conclusions [see citations in (67)]. Clinical studies have also documented significant survival enhancement with HBO₂ for extremity re-implantation and free tissue transfer, and following crush injury (15, 127). Other clinical trials have shown reductions in coronary artery re-stenosis after balloon angioplasty/stenting (105, 106), decreased muscle loss after thrombolytic treatment for myocardial infarction (31, 104, 108), improved hepatic survival after transplantation and more rapid return of donor liver function (84, 110) and reduced incidence of encephalopathy seen after cardiopulmonary bypass and following carbon monoxide poisoning (5, 128).

As is the case with wound healing, there appear to be complex and perhaps overlapping mechanisms for therapeutic effects of HBO₂ (see Fig.1). An early event associated with tissue reperfusion is adherence of circulating neutrophils to vascular endothelium by β₂ integrins. When animals or humans are exposed to HBO₂ at 2.8 to 3.0 ATA (but not to just 2.0 ATA O₂), the ability of circulating neutrophils to adhere to target tissues is temporarily inhibited (63, 70, 117, 120, 137). In animal models, HBO₂-mediated inhibition of neutrophil β₂ integrin adhesion has been shown to ameliorate reperfusion injuries of brain, heart, lung, liver, skeletal muscle and intestine, as well as smoke-induced lung injury and encephalopathy due to carbon monoxide poisoning (9, 65, 111, 114, 117, 122, 132, 134, 137). It also appears that benefits of HBO₂ in decompression sickness are related to the
temporary inhibition of neutrophil $\beta_2$ integrins, in addition to the Boyle's Law-mediated reduction in bubble volume as discussed in the introduction (78).

Exposure to HBO$_2$ inhibits neutrophil $\beta_2$ integrin function because hyperoxia increases synthesis of reactive species derived from NOS-2 and myeloperoxidase, leading to excessive S-nitrosylation of $\beta$-actin (113). This is a highly localized process occurring within neutrophils and not observed in other leukocytes, probably because of a paucity of myeloperoxidase. This modification increases the concentration of short, non-cross-linked filamentous (F)-actin, alters F-actin distribution within the cell, and it inhibits $\beta_2$ integrin clustering on the membrane surface. HBO$_2$ does not reduce neutrophil viability and functions such as degranulation, phagocytosis and oxidative burst in response to chemoattractants remain intact (61, 117, 120). Inhibiting $\beta_2$ integrins with monoclonal antibodies will also ameliorate ischemia-reperfusion injuries but in contrast to HBO$_2$, antibody therapy causes profound immunocompromise (85, 86). Probably the most compelling evidence that HBO$_2$ does not cause immunocompromise comes from studies in sepsis models, where HBO$_2$ has a beneficial effect (23, 96, 119). HBO$_2$ does not inhibit neutrophil antibacterial functions because the G-protein coupled 'inside-out' pathway for activation remains intact, and actin nitrosylation is reversed as a component of this activation process (113). The 'de-nitrosylation' mechanism in neutrophils is an area of current investigation.

Monocyte-macrophages exhibit lower stimulus-induced pro-inflammatory cytokine production after exposure to HBO$_2$. This is seen with cells removed from humans and animals exposed to HBO$_2$ and also when cells are exposed to HBO$_2$ ex vivo (12, 71, 129). The HBO$_2$ effect on monocyte/macrophages may be the basis for reduced circulating cytokine levels after endotoxin stress, as was mentioned above (43). The mechanism is unknown, but could be related to HBO$_2$-mediated enhancement of heme oxygenase-1 and heat shock proteins (HSP) [e.g. HSP 70] (35, 97).
Hence, once again, an oxidative stress response seems to occur. There are additional mechanisms involved with beneficial HBO₂ effects in reperfusion models. HBO₂ augments ischemic tolerance of brain, spinal cord, liver, heart and skeletal muscle by mechanisms involving induction of antioxidant enzymes and anti-inflammatory proteins (24, 47, 56, 66, 90, 136).

HIF-1 is responsible for induction of genes that facilitate adaptation and survival from hypoxic stresses (103), and so has been a focus of interest when examining HBO₂ therapeutic mechanisms in ischemia-reperfusion models. HIF-1 is involved with pro- as well an anti-apoptotic pathways and in brain, promotes astrocyte mediated-chemokine synthesis (3, 88). In several models, exposure to HBO₂ appears to ameliorate post-ischemic brain injury by decreasing HIF-1 expression (26, 73). When HBO₂ is used in a prophylactic manner to induce ischemic tolerance, however, its mechanism appears related to up-regulation of HIF-1 and at least one of its target genes, erythropoietin (48). Thus, as was the case in wound healing models, timing of HBO₂ application appears to influence cellular responses.

There has been a long tradition of considering HBO₂ therapy for a variety of highly virulent infectious diseases, such as necrotizing fasciitis and clostridial myonecrosis, with a view that the microorganisms involved were particularly sensitive to elevated partial pressures of O₂. Several retrospective cohort trials indicate there is a benefit to including HBO₂ with antibiotics and surgery for necrotizing fasciitis (41, 95, 131). There is only one multi-center retrospective study where a trend towards increased survival was seen in the HBO₂ group [30 % mortality (9 of 30 patients) with HBO₂ and 42 % (10 of 24 patients) without HBO₂], but this was not statistically significant. Despite this observation, the authors stated support for use of HBO₂ because of apparent selection bias between groups (19). Retrospective comparisons examining efficacy of HBO₂ in clostridial myonecrosis support its use, but again there is on-going debate (50).
With regard to mechanisms, most clinically significant anaerobic organisms are actually rather aerotolerant and thus tissue O₂ tensions, even those achievable with HBO₂, are expected to be only bacteriostatic for these organisms (68). More likely therapeutic mechanisms include impairment of exotoxin production, which is O₂-sensitive and can be inhibited at tissue partial pressures achievable with HBO₂ (50); and leukocyte killing which is improve at progressively higher O₂ tensions (75). We suggest that a broader focus may be required to elucidate the as yet unclear pathophysiology of these serious infections and the role of HBO₂. A recent study of streptococcal myonecrosis showed that host responses to even minor traumatic injuries increase expression of vimentin in muscle tissue, which mediates adhesion/sequestration of microorganisms (21). There is also a role for intravascular platelet-neutrophil aggregation with vascular occlusion in these infectious processes (20, 54). These issues are much closer to the pathophysiological events seen with disorders such as ischemia/reperfusion injuries than traditional ideas in infectious diseases. There is ample room for further investigation.

In review, oxidative stress responses triggered by HBO₂ improve outcome from a wide variety of post-ischemic/inflammatory insults. HBO₂ also improves ischemic tolerance when used in a prophylactic manner. The basis for these effects is only partially understood. Augmented synthesis of reactive species temporarily inhibits endothelial sequestration of neutrophils by inhibiting β₂ integrin function and in many tissues HBO₂ will induce antioxidant enzymes and anti-inflammatory proteins.

Summary: This brief review has highlighted some of the beneficial actions of HBO₂ and the data that indicate oxidative stress brought about by hyperoxia can have therapeutic effects. Figure 1 provides a summary of mechanisms, all of which appear to stem from elevations in reactive species. While there has been substantial advancement of the field in recent years, more work is required to establish the breadth of HBO₂ utilization in 21st century medicine. Investigations of fundamental mechanisms are
still needed, and on the clinical front, patient selection criteria must be clarified to truly make HBO2 a cost-effective treatment modality.

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References


Figure 1. Overview on therapeutic mechanisms of HBO₂. The two primary effects of HBO₂ are to reduce the volume of bubbles in the body and elevate tissue oxygen tensions. The figure outlines effects that occur due to increased production of reactive oxygen species (ROS) and reactive nitrogen species (RNS) because of hyperoxia. Other abbreviations: GFs=growth factors, VEGF=vascular endothelial growth factor, HIF-1= hypoxia inducible factor-1, SPCs=stem/progenitor cells, HO-=heme oxygenase-1, HSPs=heat shock proteins.
HBO₂ → BUBBLE VOLUME REDUCTION

ELEVATED CELLULAR O₂ LEVELS

INCREASED ROS & RNS

SPCs MOBILIZATION FROM BONE MARROW & INCREASED HIF-1/2 CONTENT

INCREASE WOUND GFs:
- SDF-1
- ANGIOPONTIN
- BASIC FIBROBLAST GF
- TRANSFORMING GF β₁
- VEGF (via HIF-1)

NEUTROPHIL S-NITROSYLATION

LOWER MONOCYTE CHEMOKINE SYN’ESIS

WOUND NEOVASCULARIZATION/HEALING

IMPAIRS β₂ INTEGRIN FUNCTION

IMPROVED POST-ISCHEMIC TISSUE SURVIVAL

β₁

ISCHEMIC PRE-CONDITIONING CHANGES IN HO-1, HSPs, HIF-1

β₂

IMPACT ON MONOCYTE CHEMOKINE SYN’ESIS

IMPACT ON WOUND NEOVASCULARIZATION

HIF-1

β₂ INTEGRIN FUNCTION IMPAIRED