Protection of mitochondrial function and improvement in cognitive recovery in rats treated with hyperbaric oxygen following lateral fluid-percussion injury

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Objective. Hyperbaric oxygen (HBO2) has been shown to improve outcome after severe traumatic brain injury, but its underlying mechanisms are unknown. Following lateral fluid-percussion injury (FPI), the authors tested the effects of HBO2 treatment as well as enhanced normobaric oxygenation on mitochondrial function, as measured by both cognitive recovery and cellular adenosine triphosphate (ATP) levels.

Methods. Adult male Sprague–Dawley rats were subjected to moderate lateral FPI or sham injury and were allocated to one of four treatment groups: 1) FPI treated with 4 hours of normobaric 30% O2; 2) FPI treated with 4 hours of normobaric 100% O2; 3) FPI treated with 1 hour of HBO2 plus 3 hours of normobaric 100% O2; and 4) sham-injured treated with normobaric 30% O2. Cognitive outcome was assessed using the Morris water maze (MWM) on Days 11 to 15 after injury. Animals were then killed 21 days postinjury to assess hippocampal neuronal loss. Adenosine triphosphate was extracted from the neocortex and measured using high-performance liquid chromatography. The results showed that injured animals treated with HBO2 or normobaric 100% O2 alone had significantly higher levels of cerebral ATP as compared with animals treated using normobaric 30% O2 (p < 0.05). The injured animals treated with HBO2 had significant improvements in cognitive recovery, as characterized by a shorter latency in MWM performance (p < 0.05), and decreased neuronal loss in the CA2/3 and hilar regions as compared with those treated with 30% or 100% O2 (p < 0.05).

Conclusions. Both hyperbaric and normobaric hyperoxia increased cerebral ATP levels after lateral FPI. In addition, HBO2 treatment improved cognitive recovery and reduced hippocampal neuronal cell loss after brain injury in the rat.

Key Words • traumatic brain injury • fraction of inspired oxygen • hyperbaric oxygen treatment • cognitive function • adenosine triphosphate • hippocampal cell count • rat

Traumatic brain injury consists of primary and secondary insults that result in cell death and dysfunction. The primary insult is due to transient mechanical tissue damage, whereas the secondary insults consist of delayed interrelated biochemical events that lead to ischemia, hypoxia, elevated ICP, reduced cerebral blood flow, excitotoxicity, and metabolic failure.2 Data from both clinical and experimental studies have implicated the hippocampus as an important structure for memory.12,50 This structure has been found to be particularly vulnerable to many types of secondary insults, such as ischemia, hypoxia, hypoglycemia, and experimental brain injury.3,12,18,27,44,47 Among these injuries, cerebral hypoxia and ischemia are believed to contribute significantly to the secondary insult process even after the initial traumatic insult has ceased.

Hypoxia and ischemia cause a shift away from aerobic metabolism and limit much of the aerobic ATP production, with a shift to glycolysis, resulting in an enormous rise in cerebral lactate levels, which in turn lowers brain pH. An imbalance between energy demand and availability results in the consequent ischemia-like state, with a reduction in the ATP available to neurons and glia.22 Given that hypoxia and ischemia are major pathophysiological complications after TBI, it is not surprising that 80 to 90% of patients who die of head injury demonstrate ischemic changes on histopathological examination of brain tissue.18 It has been demonstrated in human studies that ischemia partly

Abbreviations used in this paper: ADP = adenosine diphosphate; AMP = adenosine monophosphate; ANOVA = analysis of variance; atm = atm absolute; ATP = adenosine triphosphate; DHR = dihydrodichlorofluorescein; FPI = fluid-percussion injury; HBO2 = hyperbaric oxygen; HPLC = high-performance liquid chromatography; ICP = intracranial pressure; MWM = Morris water maze; NAD = nicotinamide adenine dinucleotide; NADH = reduced form of nicotinamide adenine dinucleotide; ROS = reactive oxygen species; SEM = standard error of the mean; TBI = traumatic brain injury.
results from a severe reduction in cerebral blood flow early after the primary injury. Furthermore, arterial hypoxia doubles the mortality rate in these hypoxic patients. For this reason, the manipulation of brain O₂ delivery may be a means of treating cerebral hypoxia.

There are several ways to enhance O₂ delivery, including increasing cerebral perfusion pressure with amines as well as increasing relative blood flow. Methods that raise cerebral perfusion pressure may have inherent complications, such as increasing the possibility of intracranial hemorrhage or causing adult respiratory distress syndrome and acute renal failure. In the current study we used methodologies that enhance O₂ solubility in plasma by either increasing the PaO₂ using HBO₂ or increasing the O₂ tension by simply increasing the inspired fraction of O₂ to 100% (normobaric hyperoxia).

In the past four decades, HBO₂ has been used in the treatment of cerebral lesions, such as those caused by experimental ischemia and human head injury. Although the potential mechanism of HBO₂ in treating TBI is not fully understood, the use of O₂ enhancement in TBI is based on the theory that mitochondrial injury impairs the production of energy substrates such as ATP and that, at least in some cells, this reaction may be reversible. Improving O₂ availability may thus stimulate the cells to recover function by reactivating them metabolically, thereby allowing restoration of ion pumping, resting membrane potential, electrical activity, and normalization of astrocyte volume.

We have previously demonstrated that HBO₂ treatment can increase injured brain tissue PO₂ immediately after injury, enhance the mitochondrial redox potential at 4 hours postinjury, and increase brain tissue O₂ consumption. To further explore the therapeutic potential of HBO₂, we hypothesized that if it were able to improve cerebral aerobic metabolism after TBI, it would do so by increasing cerebral ATP levels. High-performance liquid chromatography was used to measure ATP levels in cerebral tissue. Furthermore, we evaluated the effect of HBO₂ treatment on cognitive recovery by using the MWM test and assessed hippocampal neuronal cell loss by using an unbiased stereological method. We also measured free radical production following hyperoxia treatment. We have thus used several of the most highly specific assessment methods available for TBI studies in animals to validate the anatomical and mechanistic bases of acute oxygenation therapies in diffuse TBI.

**Materials and Methods**

**Animal Population**

Adult male Sprague–Dawley rats (Harlan, Inc.) weighing 290 to 350 g were used in this study. Rats were housed singly in an environmentally controlled room in the animal facility, with free access to food and water, and were maintained on a 12/12-hour light/dark cycle. All experiments were approved by the Institution of Animal Care and Use Committee of Virginia Commonwealth University in accordance with all guidelines for animal use in research. Ninety-two animals were used and divided into four experimental groups: 1) sham-injured animals receiving normobaric 30% O₂, 22 rats; 2) injured animals receiving normobaric 30% O₂, 23 rats; 3) injured animals receiving HBO₂, 23 rats. These animals were allocated to three experiments: 1) ATP production, four rats from each experimental group; 2) cognition, 10 rats from each experimental group; and 3) free radical generation: eight from the sham-injured group, 10 from the 100% O₂ group, nine from the HBO₂ group, and nine from the 30% O₂ group.

**Induction of Anesthesia**

Animals received a gas mixture of O₂ and N₂ via mechanical ventilation. We used 30% O₂ and 70% N₂ as nonexperimental gases because this mixture is close to that used in an intensive care unit in which most patients with TBI are treated. Moreover, 30% O₂ is relatively close to the room air equivalent of 21%. Isoflurane anesthesia was provided via the carrier gas mixture and adjusted according to the protocol described later in this paper.

**Surgical Procedures**

The lateral FPI model has been previously described in detail. Briefly, rats were anesthetized using 4% isoflurane in a carrier gas mixture of 70% N₂ and 30% O₂. The animals were immediately intubated, received mechanical ventilation with isoflurane reduced to 2%, and then were secured in a stereotactic frame (Kopf Instruments). The animal’s core temperature was maintained at 37.0 ± 0.5°C by using an animal homeothermic heating system. A midline scalp incision was made, and the soft tissue was reflected to reveal the bregma, lambdoid, and sagittal suture lines as well as the parietal ridges. A 4.8-mm craniotomy was trephined into the left parietal bone, with the anterior edge of the craniotomy being located at the bregma ~4.0 mm and centered between the sagittal suture and the parietal ridge. Two 1/16th-in stainless steel screws were anchored in bur holes 1 mm rostral to the bregma and 1 mm caudal to the lambdoid suture lines. A modified Luer-Loc needle hub (machine cut to an 8-mm length and a 2.6-mm inside diameter) was placed over the intact dura mater and bonded to the skull with α-cyanoacrylate glue. The hub and screws were then stabilized with dental acrylic.

After the dental acrylic sufficiently hardened, the animal was briefly removed from anesthesia to administer a 2.25 ± 0.04-atm fluid-percussion pulse and then reconnected to the anesthesia. This injury level was used to produce a moderately severe injury that is generally associated with prolonged cognitive deficits. After the injury, the cranial connector assembly was removed from the skull, and the scalp wound was sutured closed. Sham-injured animals underwent identical anesthesia and surgeries but did not actually receive the FPI.

**Hyperoxia Treatment: HBO₂ and 100% O₂ Without HBO₂**

Experimental hyperoxia was induced using 4 hours of normobaric 100% O₂ alone or 1 hour of HBO₂, followed by 3 hours of normobaric 100% O₂. In the HBO₂ treatment group, following the injury, animals received ventilation at 30% O₂ for 15 minutes before being transferred to a hyperbaric research chamber (model B11-22, Reimers Engineering, Inc.) pressurized to 1.5 ata with 100% O₂. Animals were then allowed to remain in the chamber breathing 100% O₂ at less than 1 ata for another 3 hours. The O₂ concentration in the chamber was monitored with an O₂ meter (Mini Ox 3000, MSA Medical Products) to ensure 100% O₂ throughout the treatment. In the normobaric 100% O₂ treatment group (without HBO₂), following the injury, the animals received ventilation at 30% O₂ for 15 minutes before being transferred to the same chamber filled with 100% O₂ at 1 ata and remaining there for 4 hours. The animals were not restrained or anesthetized while in the chamber.

**Cognition Testing**

Morris Water Maze. The MWM test was performed as a measure of cognitive function following an acquisition paradigm on postinjury Days 11 to 15. Briefly, the rats underwent four trials per day for 5 consecutive days. On each trial, the rats were placed in the pool at one of the four start locations (south, west, north, and east) in a randomized fashion. The animal’s movements within the tank were recorded and analyzed with a video tracking system (Polytrack 4, San Diego Instruments). This tracking equipment allowed for the analysis of both the time to reach the goal platform and the swim speed. The time to find the platform was the primary dependent variable for the assessment of cognitive performance. The swim speed was calculated to ensure that the cognitive performance was not confounded.
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by motor deficits that could adversely affect the swimming performance.

Stereological Cell Quantification. The number of neurons in the hippocampal subregions was determined with stereological methods by applying the Olympus image system CAST program. Every third coronal hippocampal section 180 μm apart was examined. Nissl-stained neurons in the CA1, CA2/3, and hilar regions were counted within the counting frame, ignoring the cells in the upper- and lowermost focal planes while focusing through the thickness of the sections to avoid oversampling errors.3

Quantification of ATP

To examine the early effects of hyperoxia on tissue metabolism, ATP was measured 1 hour after treatment following a previously published protocol.1 Fifteen minutes after injury, the rats received normobaric 30% O₂ normobaric 100% O₂, or HBO2 treatment for 1 hour. At the end of the treatment, while the animal was under deep anesthesia, the skull was opened and the brain was exposed between the lambdoid and coronal sutures, and the parietal ridges. The neocortical tissue containing the site of injury was quickly removed and dropped into liquid N₂. The animal was then killed while under the same deep anesthesia.

Acid Extraction. Each sample was removed from the liquid N₂ and, while still frozen solid, was quickly crushed with a pestle and weighed. The tissues (20 to 50 mg) were then placed in 75 × 10-mm glass tubes containing 0.4 ml of 12% trichloroacetic acid and homogenized in a custom glass homogenizer for 30 minutes. At the end of 30 minutes, the tubes were centrifuged for 10 minutes at 3000 G at 10°C, and the supernatants were transferred to clean tubes. To neutralize the samples, a 3:1 mixture of R13 Freon and tri-n-octylamine was made and applied in a fume hood. Next, 0.8 ml of the mix was added to the trichloroacetic acid extract and mixed on a vortexer for 2 minutes to combine the phases. The samples were centrifuged at 3000 G for 10 minutes at 10°C to separate the phases. The upper layer containing the neutralized extract was placed in a microcentrifuge tube, snap frozen in liquid N₂, and stored at −80°C until analyzed. The Freon/tri-n-octylamine mix was absorbed into activated charcoal and discarded in accordance with Environmental Protection Agency rules.

High-Performance Liquid Chromatography System. The measurement of adenine nucleotides and NAD+ was performed using HPLC. The HPLC standards containing known amounts of adenine nucleotides, nucleosides, purine bases, and NAD+ or unknown samples were injected into a Waters Intelligent Sample Processor HPLC system (model 710B, Waters Associates). The system included an Alltech 101 solvent selector (Alltech Association) coupled to a Waters 6000A solvent delivery system. Separation of the metabolites was achieved using a NOVA-Fak-A C18 column (10 × 8 mm, 5-μm particle size) inside a Waters Radial Compress Module 100-H. Metabolites were measured and quantified using a Waters 490 four-channel absorbance detector at a wavelength of 254 nm coupled to a Waters 730 integrator.

Separation Using HPLC. Step-gradient elution was performed using a three-solvent protocol with a flow rate of 1.5 ml/minute. High-performance liquid chromatography-grade ammonium phosphate (100 mmol/L) buffered at pH 4.7 allowed the sequential elution of ADP, AMP, xanthine, and ATP. The second solvent, 7% methanol, eluted NAD+. The third solvent, 40% methanol, allowed the final elution of inosine and adenosine. All of the data were expressed as nanomoles per gram tissue wet weight.

Histological Studies

A randomly selected subset of animals (four animals/group) was used in a histological analysis. At 21 days postinjury, the animals were deeply anesthetized and transcardially perfused with 150 ml of phosphate-buffered saline followed by 150 ml of 4% paraformaldehyde. The brains were removed from the skull and fixed in 4% paraformaldehyde at 4°C for 48 hours. A small wedge (remote from the hippocampus) in the left hemisphere was made with a dissecting blade to ensure accurate recognition of the left and right hemispheres for subsequent tissue processing. Coronal 60-μm sections through-out the entire length of the hippocampus were cut using a vibratome (VT1000s, Leica). Every third section was mounted on a microscope slide (Superfrost/Plus) and stained for Nissl substance with cresyl violet, for a total of 10 sections per brain.

Mitochondrial Free Radical Generation

To determine whether injury and O₂ treatment induced free radical formation, the oxidation-sensitive dye, DHR (Molecular Probes) was used to measure the relative mitochondrial ROS generation.4 This lipophilic, mitochondria-specific dye is oxidized by peroxynitrite and peroxide to form rhodamine 123, which can fluoresce and thus be detected. For rhodamine 123 fluorescence measurement, mitochondria-enriched samples were prepared following a previously published method.6 Briefly, after completing treatment, the animals were perfused with ice-cold phosphate-buffered saline, and the neo-cortex under the craniotomy was removed and homogenized in an extracting buffer (0.32 mol/L sucrose, 20 mmol/L HEPEs, and 2 mmol/L dipotassium ethylenediaminetetraacetic acid, pH 7.2). The homogenate was centrifuged twice at 2000 G, and the supernatant was collected. After further centrifugation at 11,600 G two times, the pellet was collected, resuspended in buffer, and stored at −80°C until used. Approximately 60 μg of the mitochondria-enriched fraction was incubated with the DHR for 30 minutes at 37°C, for a final concentration of 5 μmol/L of the mitochondria-enriched fraction. The samples were then centrifuged at 11,200 G and washed twice in DHR-free buffer. The pellets were then resuspended in extracting buffer and 100-μl aliquots were transferred to a Nunc 96-well uncoated black plate for fluorescence quantification on a BMG FLUOstar Galaxy plate reader (485 nm excitation and 520 nm emission, fluorescence). All samples were run in duplicate, and ROS generation was expressed as relative levels of rhodamine 123 per microgram protein. Because rhodamine 123 measures only the production of peroxide and peroxynitrite, this methodology measured only a small portion of the entire free radical generation spectrum.

Statistical Analysis

The MWM performances were analyzed using a 4 (number of groups) × 5 (number of days) split-plot ANOVA. To determine specific group differences, the Duncan multiple range test was used. The ATP data were evaluated using an ANOVA, and a post hoc Student’s t-test was applied to compare the group means. A probability value less than 0.05 was considered statistically significant in our analysis of the MWM and ATP data. Stereological data were evaluated using an ANOVA followed by a post hoc Student’s t-test for comparing the group means. In all these analyses, a probability value less than or equal to 0.05 was considered statistically significant.

All data are expressed as the means ± SEM for each group.

Results

Measurements of ATP

To examine the early effect of hyperoxia treatment on mitochondrial function following TBI, ATP was extracted and measured using HPLC. We found significant reductions in cerebral ATP levels in injured animals (lateral FPI) compared with those in sham-injured animals (p ≤ 0.05). There were also corresponding significant reductions in ADP and NAD+ levels in these same animals (p ≤ 0.05). The AMP levels were slightly increased in injured animals on 30% O₂, compared with sham-injured animals (Fig. 1). When examining the effect of 1 hour of hyperoxia treatment, ATP levels were significantly elevated in both the normobaric 100% O₂ and the HBO₂-treated groups compared with levels in injured animals that had received 30% O₂. Both hyperoxia treatments increased ATP to levels near that in the sham-injured rats (p ≤ 0.05). The AMP levels were significantly reduced in injured animals that had received either hyperoxic treatment when compared with the
animals that had received 30% O₂ (p ≤ 0.05). The ADP and NAD+ levels in both hyperoxia-treated groups were slightly higher than those in the 30% O₂–treated group and were similar to those in the sham-injured animals.

Morris Water Maze Assessment

At 11 to 15 days postinjury, cognitive deficits were tested using the MWM. The results showed that the injured animals that received only 30% O₂ (mean time to reach the platform 90.5 seconds) took a significantly longer time to reach the goal compared with rats in the other groups (100% O₂ treatment, mean time 77.4 seconds; HBO₂ treatment, mean time 65.5 seconds; and sham-injured group, mean time 42.2 seconds). Similarly, the injured animals treated with normobaric 30% O₂ took a longer time to find the goal than the injured animals treated with HBO₂. Moreover, the injured animals treated with HBO₂ took a longer time than the sham-injured group but less time than the other two treatment groups to find the goal (Fig. 2). The ANOVA analysis of goal latencies revealed a significant main effect of group [F(3,54) = 48.7, p ≤ 0.001], day [F(4,216) = 445.6, p ≤ 0.01], and group × day [F(12,216) = 6.5, p ≤ 0.001].

Histological Study

Four rats in each group were randomly picked to evaluate neuronal cell loss in the hippocampus. Cresyl violet stains intact neurons. Those neurons undergoing early degeneration would have fully degenerated and been removed by 21 days after injury. Neurons in the CA1, CA2/3, and hilar regions in the ipsilateral hippocampus were counted using an unbiased stereological method. We found no significant cell loss in the CA1 area in all three injured rat groups compared with that in the sham-injured group (data not shown). In the CA2/3 area, all injured groups had significant cell loss compared with that in the sham-injured animals (p ≤ 0.05). However, animals that had been treated with HBO₂ demonstrated significantly less neuronal cell loss compared with that in animals that had received normobaric 30% or normobaric 100% O₂ treatment only (p ≤ 0.05; Fig. 3). In addition, there was no significant difference in neuronal cell counts between animals that received 30% O₂ and those that received 100% O₂. In the hilar region, all injured animals had significant neuronal cell loss as compared with that in the sham-injured group (p ≤ 0.05; Fig. 4). However, injured animals treated with HBO₂ had significantly less neuronal cell loss compared with that in injured animals treated with 30% O₂ (p ≤ 0.05). There was no significant difference among injured groups treated with 30% O₂ and those treated with 100% O₂.

Mitochondrial Free Radical Formation

The ability of the mitochondria to produce ROS, specifically peroxide and peroxynitrite, was not significantly altered in injured rats compared with sham-injured controls at 1 or 4 hours, as measured by rhodamine 123 fluorescence. Likewise, no significant changes in peroxide and peroxynitrite were demonstrated based on treatment with 30%, 100% O₂, or HBO₂ plus 100% O₂ at 1 or 4 hours in both sham-injured and injured animals (Table 1).

Discussion

The use of HBO₂ to treat TBI remains controversial. Conversely, its effectiveness has been shown for conditions such as decompression sickness, anaerobic infections, tis-
sue hypoxia, and diabetic wound healing. In a landmark phase IIB controlled study, Rockswold et al. showed improved outcome and lower ICP in a group of 168 patients with severe TBI treated with HBO$_2$ every 8 hours for up to 14 days after injury. Nevertheless, the widespread adoption of HBO$_2$ for the treatment of TBI is not established. We have shown that normobaric hyperoxia (100% fraction of inspired O$_2$ for 24 hours) was beneficial in two case–control cohort studies. Yet, the mechanisms for these beneficial effects remain poorly understood. In the present study, we demonstrated that HBO$_2$ treatment in the rat, even for only 1 hour after moderate experimental FPI, can preserve cerebral ATP levels, improve cognitive recovery, and reduce hippocampal neuronal cell loss, thus providing experimental data to validate the efficacy of this treatment.

**Effect of Hyperoxia on Cerebral Metabolism**

After TBI, compromised O$_2$ delivery can result in impaired mitochondrial respiration, leading to a shift from aerobic to anaerobic metabolism with increased lactate production/accumulation and reduced ATP production. Following TBI, a reduction in local blood flow caused by diverse mechanisms, such as microvessel compression, endovascular and perivascular edema, hypovolemic shock, and cerebral vasospasm, could contribute to this mitochondrial ATP reduction. The acute decrease in the ATP/ADP ratio that arises from an increase in cytosolic ADP and a reduction in tissue ATP concentrations indicates a loss of energy production at a time when an increased demand for energy is occurring after acute brain injury.

In the current study, we focused our efforts on determining any adverse effect on mitochondrial ATP production early after TBI. We have shown that a moderate FPI can cause a significant reduction in cerebral ATP levels as early as 1 hour postinjury, indicating that mitochondrial function can be suppressed within this time frame, a finding consistent with data from other reports. However, injured animals treated with either HBO$_2$ or 100% O$_2$ have shown significantly preserved mitochondrial function, as measured by cerebral ATP levels, compared with injured animals that received 30% O$_2$. The beneficial effects of HBO$_2$ and hyperoxia have thus already been proven in several clinical studies. In a microdialysis study in which 52 patients with TBI had been treated with normobaric 100% O$_2$, reduced extracellular fluid lactate and increased extracellular fluid glucose were observed, suggesting that anaerobic glycolysis can be improved with normobaric 100% O$_2$ treatment.

Rockswold and colleagues have shown that HBO$_2$ treatment can improve aerobic metabolism in severely brain-injured patients by increasing the cerebral metabolic rate of O$_2$ and decreasing cerebrospinal fluid lactate levels. The regulation of the citric acid cycle by NADH may par-

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**TABLE 1**

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<th>Parameter</th>
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* Values represent the relative rhodamine 123 fluorescence per microgram of protein ± SEM.
tially explain the effect of HBO₂ and hyperoxia. High concentrations of NADH have long been known to reduce the metabolic rate of the citric acid cycle. Hyperbaric O₂ may lead to an increase in ATP production via the oxidation of mitochondrial NADH and consequently the production of NAD⁺ thereby donating electrons to the electron transport chain. In turn, NAD⁺ has the ability to increase the functional rate of the citric acid cycle, thus further enhancing mitochondrial ATP generation. In the present study, the levels of NAD⁺ in both HBO₂- and normobaric O₂-treated groups supports this phenomenon. However, the exact mechanisms of this increase in mitochondrial function due to enhanced tissue O₂ tension remain unclear and require further investigation.

Interestingly, we found in the current study that the ATP levels in the rats treated with normobaric hyperoxia (100% O₂) were higher than those in the HBO₂-treated group, although the difference did not reach statistical significance. This observation suggests that early treatment with normobaric O₂ may have beneficial effects on mitochondrial function in return for much less effort in comparison with HBO treatment. In either case, what remains unclear is whether the preservation of cerebral ATP levels after TBI can be maintained for longer than 1 hour. We do know, however, that the administration of 100 mmol/L lactate over the course of 3 hours does result in a significant increase in ATP levels 3 hours after FPI and, because lactate increases mitochondrial O₂ consumption, that there is likely to be a concomitant increase in ATP production. Nevertheless, further studies to determine the effect of hyperoxia treatment on the duration of cerebral ATP production after TBI are necessary.

**Effect of Hyperoxia on Cognitive Function**

Following FPI, mitochondrial damage can contribute to the progressive cell death observed in the parietotemporal cortex and the CA3 region of the hippocampus. In the current study, we found that early HBO₂ treatment improves cognitive recovery and reduces neuronal cell loss in the hippocampus in rats following a moderate lateral FPI. In the MWM test, injured animals in all treatment groups (normobaric 30% O₂, normobaric 100% O₂, and HBO₂) took a significantly longer time to find the hidden platform as compared with the sham-injured animals; however, the HBO₂-treated animals had a significantly shorter latency than the injured animals in the other two treatment groups. These results demonstrated that HBO₂ treatment can improve cognitive recovery in rats following FPI. Nevertheless, injured animals treated with 100% O₂ alone also had a significantly shorter latency as compared with injured animals receiving 30% O₂. This finding implies that normobaric hyperoxia is also beneficial and is consistent with data in previous studies demonstrating that normobaric hyperoxia has a positive effect on brain-injured and ischemic animals. Moreover, it is also consistent with data in clinical studies showing improvements in ICP and outcome after severe TBI in humans treated with normobaric hyperoxia.

**Effect of Hyperoxia on Hippocampal Cell Survival**

Neuronal cell loss in the hippocampus has been suggested to be the major mechanistic link to cognitive impairment after experimental TBI. In the current study, we quantified neuronal cell survival in the CA1, CA2/3, and hilar regions of the ipsilateral hippocampus at 21 days after injury so that uniform cell morphometry criteria could be applied; all lethally damaged neurons would be expected to have passed through all the states of necrotic or apoptotic cell death before this 21 day time point. Such information is crucial, because many other therapeutic interventions in animal models of TBI have been focused on the extent of neuronal degeneration as an end point. In the areas of CA2/3 and the hilus, a significant decrease in the number of neurons was observed in all injured animals compared with the sham-injured animals. Note, however, that animals treated with HBO₂ had significantly less neuronal cell loss in both areas. This result clearly demonstrates that HBO₂ treatment can reduce neuronal cell loss in the hippocampus, which contributes to the improved cognitive recovery observed in the MWM performance.

Our data suggest that HBO₂ treatment has a greater beneficial effect on the injured animals than normobaric 100% O₂ alone. The positive results with normobaric 100% O₂ imply an incremental effect rather than an all or nothing effect. Using the same lateral FPI model, Daugherty and associates have documented that HBO₂ produces brain tissue PO₂ levels 10 times greater than those induced by normobaric 30% O₂ (30 mm Hg compared with 300 mm Hg) and three times greater than those generated by normobaric 100% O₂ (100 mm Hg compared with 300 mm Hg). Rockswold and colleagues have demonstrated the same differential brain tissue PO₂ levels in humans (unpublished data). Note that HBO₂ at 1.5 ata increases the amount of dissolved O₂ in the plasma from 0.3 ml/dl in air to 3.2 ml/dl, which is on the order of 10 times. Given that the macrocirculation as well as the microcirculation can act as diffusion barriers to O₂ delivery to brain tissue, the brain tissue PO₂ levels achieved may be critical to mitochondrial function. Hyperbaric O₂ greatly increases the O₂ diffusion gradient from the lungs to blood to brain tissue. Nonhemoglobin O₂ transport may be more significant than previously thought. If, as it appears, the presence of O₂ induces the mitochondria to begin to function, brain tissue PO₂ levels may be critical. This finding could well explain the more robust effect of HBO₂ in the model of lateral FPI to the brain compared with normobaric 100% O₂.

**Effect of Hyperoxia on Mitochondrial Free Radical Production**

Data from several published reports attest to various increases in O₂ free radical end products after injury. In most of these studies, however, high pressures (for example, > 3.0 ata) have been used. Observed differences may also be due to the selectivity of the dye and sample preparation. In the present study, the lack of significant alterations in rhodamine 123 fluorescence by HBO₂ or normobaric 100% O₂ treatment compared with 30% O₂ in injured animals suggests that the ability of mitochondria to generate O₂ free radicals may not be significantly enhanced by either treatment. This result supports our previous findings that hyperoxia does not significantly enhance tissue hydroxyl radical production, as determined by the salicylate trapping method. In another study, free radical formation was not increased in normal brain with HBO₂ treatment at...
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3 ata, unless 100% O2 was added for a sufficiently long period, which suggests a possible free radical formation threshold. Therefore, the combination of very high hyperbaric pressures and the prolonged use of hyperoxia may limit the usefulness of chamber pressures for HBO, treatment with 100% O2; hence, the use of 1.5 ata is seen as a major advantage. Dihydrorhodamine 123 is sensitive to the production of peroxide and peroxynitrite but not to superoxide (O2−) or nitric oxide. Therefore, the current findings do not exclude the possibility of increasing production of other radicals or of free radical generation from other important cellular sources other than mitochondria, for example, from the arachidonic acid pathways in the cytosol.

Conclusions

The results of this study show that early hyperbaric and normobaric O2 therapies have significant beneficial effects following head injury. Both normobaric 100% O2 and HBO increased ATP levels in the injured rat brain to levels close to those found in sham-injured animals. Neither hyperbaric nor normobaric O2 treatment significantly affected the ROS peroxide and peroxynitrite in sham-injured and injured rats. However, HBO-treated injured rats showed a significantly shorter latency on the MWM test than the injured rats treated with 100% O2 alone. Moreover, the combined treatments of 100% O2 and HBO significantly preserved more hippocampal neuronal cells in the CA2/3 and hilar regions than 100% O2 alone after injury. These results provide a mechanistic basis for both of these treatment modalities and support the findings of previous studies in humans. Additional studies to isolate the enzymatic and biochemical sites of action of increased O2 tension within the mitochondria are needed and warrant further clinical trials with hyperoxia, with and without HBO2.

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