A prospective, randomized Phase II clinical trial to evaluate the effect of combined hyperbaric and normobaric hyperoxia on cerebral metabolism, intracranial pressure, oxygen toxicity, and clinical outcome in severe traumatic brain injury

Clinical article

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Object. Preclinical and clinical investigations indicate that the positive effect of hyperbaric oxygen (HBO₂) for severe traumatic brain injury (TBI) occurs after rather than during treatment. The brain appears better able to use baseline O₂ levels following HBO₂ treatments. In this study, the authors evaluate the combination of HBO₂ and normobaric hyperoxia (NBH) as a single treatment.

Methods. Forty-two patients who sustained severe TBI (mean Glasgow Coma Scale [GCS] score 5.7) were prospectively randomized within 24 hours of injury to either: 1) combined HBO₂/NBH (60 minutes of HBO₂ at 1.5 atmospheres absolute [ATA] followed by NBH, 3 hours of 100% fraction of inspired oxygen [FiO₂] at 1.0 ATA) or 2) control, standard care. Treatments occurred once every 24 hours for 3 consecutive days. Intracranial pressure, surrogate markers for cerebral metabolism, and O₂ toxicity were monitored. Clinical outcome was assessed at 6 months using the sliding dichotomized Glasgow Outcome Scale (GOS) score. Mixed-effects linear modeling was used to statistically test differences between the treatment and control groups. Functional outcome and mortality rates were compared using chi-square tests.

Results. There were no significant differences in demographic characteristics between the 2 groups. In comparison with values in the control group, brain tissue partial pressure of O₂ (PO₂) levels were significantly increased during and following combined HBO₂/NBH treatments in both the noninjured brain and pericontusional brain (p < 0.0001). Microdialysate lactate/pyruvate ratios were significantly decreased in the noninjured brain in the combined HBO₂/NBH group as compared with controls (p < 0.0078). The combined HBO₂/NBH group’s intracranial pressure values were significantly lower than those of the control group during treatment, and the improvement continued until the next treatment session (p < 0.0006). The combined HBO₂/NBH group’s levels of microdialysate glycerol were significantly lower than those of the control group in both noninjured and pericontusional brain (p < 0.001). The combined HBO₂/NBH group’s level of CSF F2-isoprostane was decreased at 6 hours after treatment as compared with that of controls, but the difference did not quite reach statistical significance (p = 0.0692). There was an absolute 26% reduction in mortality for the combined HBO₂/NBH group (p = 0.048) and an absolute 36% improvement in favorable outcome using the sliding dichotomized GOS (p = 0.024) as compared with the control group.

Conclusions. In this Phase II clinical trial, in comparison with standard care (control treatment) combined HBO₂/NBH treatments significantly improved markers of oxidative metabolism in relatively uninjured brain as well as pericontusional tissue, reduced intracranial hypertension, and demonstrated improvement in markers of cerebral toxicity. There was significant reduction in mortality and improved favorable outcome as measured by GOS. The combination of HBO₂ and NBH therapy appears to have potential therapeutic efficacy as compared with the 2 treatments in isolation. Clinical trial registration no.: NCT00170352 (ClinicalTrials.gov). (http://thejns.org/doi/abs/10.3171/2013.2.JNS121468)

Key Words • hyperbaric oxygen • normobaric hyperoxia • traumatic brain injury • cerebral metabolism • intracranial pressure • oxygen toxicity • clinical outcome

The enormous negative social and economic impact of TBI throughout the world cannot be overemphasized. The major issue is premature death and disability both in civilian and military populations. Conservative estimates of the prevalence of long-term disability due to TBI in the United States are well over 3 million people. The economic toll of TBI exceeds $60 billion per year.¹⁸

Our previous investigations of HBO₂ in the treatment of severe TBI strongly suggest that the beneficial effect
demonstrated does not occur during the treatment but in the hours following the treatment. Experimental investigations also support the concept of using HBO2 followed by continued increased O2 at normobaric pressures as a single treatment. These studies have documented significant improvement in mitochondrial function, ATP production, reduced hippocampus cell loss, and functional recovery following a combined HBO2/NBH treatment as compared with NBH alone or control animals. The case for evaluating the combination of HBO2 and NBH as a single treatment appeared compelling. The 2 treatments in tandem are potentially synergistic.

The goal of this study was to evaluate cerebral metabolism, ICP, potential O2 toxicity, and clinical outcome during a prospective, randomized Phase II clinical trial comparing a combined treatment of HBO2/NBH to standard care in patients with severe TBI. This study was a subsequent supplement to a larger prospective, randomized clinical trial. This report differs from that previously published study in that O2 delivery and cerebral metabolism were studied in the pericontusional areas of some patients and clinical outcome was assessed at 6 months using the GOS; moreover, in the present study, HBO2 and NBH were evaluated in combination rather than separately.

Methods

This study was registered with the ClinicalTrials.gov database (http://clinicaltrials.gov), and its registration number is NCT00170352.

Forty-two patients treated for severe TBI at the Hennepin County Medical Center, a Level I trauma center, were entered into a prospective randomized Phase II clinical trial to evaluate the mechanisms of action of hyperoxia on cerebral metabolism, ICP, O2 toxicity, and clinical outcome. This study was a subsequent supplement to a larger prospective, randomized clinical trial. The protocol for this study was approved by the Human Subjects Research Committee at our institution. All patients had sustained severe TBI as defined by a GCS score of 8 or less after resuscitation. This score was determined when no effects from paralytic agents, sedation, alcohol, and/or street drugs were present. Patients were entered into the study within 24 hours of their injury. Patients also were entered into the study if they were admitted to the hospital with a mild or moderate TBI and deteriorated to a GCS score of 2 in accordance with the classification system of Traumatic Coma Data Bank.

**Inclusion Criteria**

- All closed-head trauma victims with GCS score of 3–8 after resuscitation, with effects from paralytics, sedation, alcohol &/or street drugs
- HBO2 treatment to begin within 24 hrs after injury
- Admission to hospital with mild or moderate brain injury & deterioration within 48 hrs
- CT scan score ≥ 2 in accordance with classification system of Traumatic Coma Data Bank

**Exclusion Criteria**

- Bilateral fixed midposition pupils
- Severe pulmonary injury requiring FiO2 > 50% &/or PEEP > 10 cm H2O to maintain adequate oxygenation
- History of severe pulmonary disease (e.g., asthma or chronic obstructive pulmonary disease)
- Fixed coagulopathy
- Pregnancy
- Severe mental retardation or prior severe brain injury or stroke
- High-velocity penetrating injury to head

with early intubation while the patient was in the emergency department, surgical evacuation of significant hematomas, continuous monitoring of ICP, and treatment of ICP greater than 15 mm Hg. All patients received prophylactic phenytoin sodium. The protocol adhered to the principles set forth in the US Code of Federal Regulations, Title 45, Part 46, Protection of Human Subjects and the World Medical Association Declaration of Helsinki.

This randomized Phase II clinical trial was designed as a 2-treatment comparison: combined HBO2/NBH treatment compared with standard care. Twenty patients received the combined HBO2/NBH treatment, which consisted of 100% FiO2 delivered for 60 minutes at 1.5 ATA followed by 3 hours at 1.0 ATA. Standard care was the control treatment, which 22 patients received. The first O2 treatment was administered as soon as the entry criteria were met and the patient’s condition was clinically stable. Subsequent treatments were given every 24 hours. Patients received 3 consecutive treatments unless they became brain dead or were consistently able to follow commands. The first 2 patients randomized to the combined HBO2/NBH arm were placed in a Class A, 4-lock multipurpose chamber (Vacuudyne, Inc.), and the next 18 in a 34-inch-diameter Bara-Med XD monoplace chamber (Environmental Tectonics Corp.). Compression to 1.5 ATA occurred at a rate of 1.0 lb/in/min and lasted 17 minutes. The patients were kept at depth for 60 minutes and underwent decompression at the same rate.

Important baseline parameters were maintained between the pretreatment and posttreatment periods. Patients in the combined HBO2/NBH treatment group were first transported to the hyperbaric chamber area, which can essentially function as an ICU. Once they were there, their baseline PaCO2, PaO2, ICP, and cerebral perfusion pressure were meticulously reestablished. The FiO2 necessary to achieve a PaO2 in the range of 90–130 mm Hg was established. The PaCO2 was kept relatively constant,

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**Table 1: Study inclusion and exclusion criteria**

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at approximately 35–40 mm Hg. The Licox catheter brain tissue PO$_2$ microprobe was calibrated in the HBO$_2$ chamber (Integra Neurosciences). The respiratory settings were kept constant for 1 hour to establish a baseline. Subsequently, the HBO$_2$ was administered. The patient was then transported back to the regular ICU where again equilibrium was established. Bilateral myringotomies were performed in all patients in the combined HBO$_2$/NBH treatment group.

**Monitored Variables**

Variables were measured before initiation of therapy and for 24 hours after therapy. There were no significant differences in baseline values between the 2 groups prior to hyperoxia treatments except for bronchial alveolar lavage (BAL) fluid IL-8 levels (see Table 2). Continuously monitored outcome variables included brain tissue PO$_2$, ICP, and microdialysate lactate, glucose, pyruvate, and glycerol levels. The brain tissue PO$_2$ measurements were downloaded into a Dell personal computer. Mean values over each 30-minute interval were calculated, except during HBO$_2$, when mean values were calculated over each 15-minute interval. Microdialysate samples were collected every hour. The recovery rate of the microdialysate was reduced during compression, so samples could not be obtained during the HBO$_2$ sessions, but they were taken during the NBH portion of the hyperoxia treatments. Intracranial pressure measurements were recorded hourly. Measurements of O$_2$ toxicity, including ventricular CSF F$_2$-isoprostanes and BAL IL-8 and IL-6, were taken before treatment and 6 hours after treatment. All monitored variables were recorded in a database (Access 2003, Microsoft Corporation) and synchronized. However, for each variable measured, some patients had missing data and so were not included in that particular statistical analysis. Differences in the numbers of patients are reflected in the figures. In all cases, the missing number of patients was approximately equivalent in the combined HBO$_2$/NBH treatment and control groups. The missing data for brain tissue PO$_2$ and microdialysate levels were attributable to probe malfunction or placement directly into injured tissue such as contusion or hemorrhage. One patient in the combined HBO$_2$/NBH group did not have ICP measurements as the ventriculostomy could not be placed because of a bilateral decompressive craniectomy.

The results of the trial allowed a direct comparison of the combined treatment of HBO$_2$ and NBH with standard care in terms of the treatment efficacy on the surrogate outcome variables as well as the patients’ functional outcome and mortality.

**Continuous Metabolic Monitoring**

A Licox catheter brain tissue PO$_2$ microprobe was used to measure brain tissue PO$_2$ and temperature (Integra LifeSciences). A CMA-70 microdialysis catheter was used to obtain all microdialysate samples (CMA Microdialysis). This catheter was inserted through the triple lumen bolt, along with the O$_2$ and temperature probes, into the frontal cortex of the brain to the desired depth of 14–24 mm. No data were collected in the first 3 hours to avoid insertion artifacts. Artificial CSF solution was infused through the probes at the rate of 0.3 μl/min. Dialysates were collected in outflow vials and frozen at –80°C. Lactate, glucose, pyruvate, and glycerol levels from the collected dialysate were measured using an off-line analyzer (CMA 600 Microdialysis Analyzer). The microdialysate L/P ratios were calculated as a marker for ischemia and the cellular redox state. Brain tissue PO$_2$ probes and microdialysis catheters were placed in either the right or left frontal lobe, whichever was least damaged. This location represented our “standard or non-injured area” of brain tissue not overtly traumatized. In 9 patients, a second brain tissue PO$_2$ probe and a second microdialysis catheter were placed in a pericontusional area or “traumatic penumbra” tissue. The pericontusional area was defined as the hypodense area around the core of the contusion or hematoma on CT scan. The position of the brain tissue PO$_2$ probes and the microdialysis catheters were checked by a CT scan as soon as possible after insertion.

**Intracranial Pressure**

Global ICP measurements were obtained with a tunneled intraventricular catheter. Any ICP greater than 15 mm Hg was treated. This treatment sequentially included mild hyperventilation, CSF drainage, administration of osmotic agents, sedation/administration of paralytic agents, and finally, decompressive craniectomy. Therapeutic intensity level (TIL) scores were recorded with ICP measurements.

| TABLE 2: Baseline mean values for combined HBO$_2$/NBH and control groups for measured values prior to treatment* |
|-----------------|-----------------|-----------------|
| Parameter       | HBO$_2$/NBH     | Control         | p Value       |
| mean brain tissue PO$_2$ (mm Hg) | 31.7 ± 3.6      | 28.9 ± 2.7      | 0.5398        |
| microdialysate lactate (mmol)       | 2.12 ± 0.25     | 2.68 ± 0.2      | 0.5877        |
| microdialysate L/P ratio         | 27.5 ± 2.4      | 26.9 ± 3.8      | 0.9490        |
| microdialysate glycerol (mmol)     | 72.5 ± 18.6     | 78.7 ± 18.6     | 0.8149        |
| ICP (mm Hg)                      | 11.3 ± 1.4      | 11.3 ± 0.9      | 0.2672        |
| ventricular CSF F$_2$-isoprostane (pg/ml) | 57.1 ± 11.4  | 49.2 ± 3.9      | 0.3538        |
| BAL IL-6 (ng/ml)                  | 7.37 ± 3.4      | 4.37 ± 1.3      | 0.2047        |
| BAL IL-8 (ng/ml)                  | 188.4 ± 49.2    | 41.2 ± 8.5      | 0.0258        |

* Means are given ± SEMs.
Oxygen Toxicity Markers

Bronchial alveolar lavage fluid samples were obtained through the endotracheal tube using sterile technique and routine respiratory care. A suction catheter (Medline Industries) was wedged into a distal lung segment, and 30 ml of sterile saline (0.9% NaCl, 37°C) was instilled and aspirated with suction into a sterile specimen collector (Allegiance Healthcare). All samples were chilled at 4°C immediately and processed within 15 minutes of collection. Samples were strained through a 60-mesh steel screen to remove mucus and then were centrifuged to remove cells, aliquoted, and frozen at −80°C until assayed for IL-8 and IL-6. The BAL IL-8 and IL-6 concentrations were determined by a commercial enzyme-linked immunosorbent assay kit per the manufacturer’s direction (BD Biosciences Pharmingen).

Cerebrospinal fluid samples taken from the birector of the ventriculostomy were chilled at 4°C immediately and processed within 15 minutes of collection. Samples were centrifuged to remove cells, aliquoted, and frozen at −80°C. The CSF F2-isoprostane content was measured using a commercial enzyme immunoassay kit (Cayman Chemical).

Outcome

The baseline severity-adjusted dichotomized GOS score was used as the primary outcome measure for assessing recovery. At 6 months, a blinded assessment using the structured GOS interview was completed with either the patient or, if the patient was unable to participate, the patient’s closest family member or legal guardian. The patient was then assigned to one of 5 categories: 1) good recovery (independent, but minor physical or mental deficits may be present); 2) moderately disabled (independent but disabled); 3) severely disabled (dependent on others); 4) vegetative; or 5) dead.52 Patients with enrollment GCS scores of 3, 4, or 5 were considered to have a favorable outcome if they achieved a GOS score of 1 (good recovery), 2 (moderate disability), or 3 (severe disability). Patients with enrollment GCS scores of 6, 7, or 8 were considered to have a favorable outcome if they achieved a good recovery or moderate disability. The dichotomized GOS score was also evaluated so that all patients had to achieve a good recovery or have only moderate disability to be considered to have a favorable outcome.

Statistical Analysis

Demographic characteristics as well as functional outcome and mortality rates across groups were compared using chi-square tests. This study was not powered as an outcome study as the primary focus was on cerebral metabolism, ICP, and oxygen toxicity.

The outcome analyses focused on the posttreatment effects because the primary study hypothesis was that the effects of hyperoxia on cerebral metabolism and ICP occur primarily after, not during, treatment. However, to examine the efficacy of HBO2 during the NBH treatment, test values obtained 1 hour after the HBO2 treatment were analyzed as well. A ratio of in- to pretreatment as well as a ratio of post- to pretreatment values was used to study differences among treatment groups for all tests except those for ICP, for which the difference between pre- and posttreatment values was used because of 0 values. All posttreatment values were obtained after the NBH portion of the combined HBO2/NBH treatment.

A mixed-effects linear model with fixed effects of treatment (group), time, day, and the treatment-time interaction (with only the significant variables kept in the final model), random patient effect, and autoregressive covariance matrix was used for testing the treatment effect. Due to the skewness of the in-treatment/pretreatment as well as the posttreatment/pretreatment ratios, natural log transformation was made to all in-treatment/pretreatment and posttreatment/pretreatment ratios. When an overall significant group or time*group interaction effect was found in the models using in-treatment/pretreatment and/or posttreatment/pretreatment ratios, post hoc orthogonal contrasts were used to determine the between-groups difference at each time point.

The graphs are simply a representation of the raw data, and the conclusions are based on the mixed-effects linear statistical model, which takes into account the longitudinal nature of the data. The treatment effect did not differ between treatment periods, so the data are shown in a binary fashion. In addition, there were no significant time*group interactions, so only the global pre- to post-treatment ratio means are shown.

Statistical significance was set at p < 0.05 in all analyses, and SAS version 9.1 (SAS Institute) was used to perform all analyses.

Results

Demographic and Clinical Characteristics

Demographic and clinical characteristics, including age, sex, mass lesion evacuations, decompressive craniectomies, Marshall CT scan scores, entry-to-study GCS scores, and episodes of intracranial hypertension were compared between the treatment and control groups (Table 3). There were no statistically significant differences (p > 0.05). All but 3 surgeries took place prior to randomization; the 3 exceptions involved 1 patient in the combined HBO2/NBH group and 2 patients in the control group, all of whom underwent decompressive craniectomy after the treatment period had begun. Lung injuries such as pulmonary contusions (4 in the combined HBO2/NBH group and 2 in the control group) and pneumo- or hemothoraces (3 in the combined HBO2/NBH group and 3 in the control group) were compared and found to be similar (p = 0.1045). There also were no differences in chest radiograph findings between the 2 groups throughout the treatment period (p = 0.7512). There were no significant between-groups differences in the number or type of polytrauma cases (p > 0.05, Table 4). There were no statistically significant differences between the number or type of brain lesions (findings of blood, contusion, or bone fracture on CT) that the combined HBO2/NBH treatment group and the control group sustained (p > 0.05, Table 5).

Cerebral Metabolic Measurements

In the combined HBO2/NBH group, patients’ brain
tissue PO$_2$ in both the noninjured and pericontusional brain rose during the treatment sessions to approximately 600% of the control group value (p < 0.0001). The mean baseline brain tissue PO$_2$ level in both groups was approximately 30 ± 4 mm Hg in the noninjured brain. During the HBO$_2$ portion of the combined HBO$_2$/NBH treatment, the mean brain tissue PO$_2$ level in noninjured brain rose to 221 ± 20 mm Hg. In comparison with the control group, the combined HBO$_2$/NBH treatment group’s mean brain tissue PO$_2$ levels remained higher by approximately 30% throughout the posttreatment period, but the improvement was only statistically significant for the first 2.5 hours following treatment (p < 0.0001). In the pericontusional brain, the mean brain tissue PO$_2$ levels remained significantly higher in the combined HBO$_2$/NBH treatment group than the control group by approximately 20% throughout the posttreatment period (p < 0.0001). Figure 1 shows brain tissue PO$_2$ in relatively noninjured brain with in-treatment and posttreatment/pretreatment ratio means.

In the HBO$_2$/NBH group, the microdialysate levels of lactate in the pericontusional brain significantly decreased below the control group levels by approximately 14% during the treatment (p = 0.0003) and for 12 hours posttreatment (p = 0.0193). There was no significant change in the noninjured brain. Figure 2 shows microdialysate lactate in pericontusional brain with intreatment and posttreatment/pretreatment ratio means.

The L/P ratio of microdialysate in the noninjured brain was significantly decreased both during treatment (p = 0.0157) and for the entire posttreatment period by approximately 5% for the combined HBO$_2$/NBH groups in comparison with the control group (p = 0.0078). The combined HBO$_2$/NBH group’s dialysate L/P ratio tended to stay below that of the control group throughout the posttreatment period in the pericontusional brain, but this difference did not reach statistical significance. Figure 3 shows microdialysate L/P ratios with posttreatment/pretreatment ratio means.
There were no significant differences in the levels of microdialysate glucose in either noninjured or pericontusional brain when the combined HBO2/NBH treatment and control groups were compared.

**Intracranial Pressure**

The ICP in the combined HBO2/NBH group was significantly lower than that of the control group during the O2 portion of the treatment. During the NBH portion of the treatment, the brain tissue PO2 remained 300% higher than in the control group until the end of treatment. For 2.5 hours after the combined HBO2/NBH treatment, the brain tissue PO2 remained significantly higher than that in the control group by ~ 50%. *p < 0.001 in comparison with the control group. Significance is based on the mixed-effects linear model. Rx = treatment.

There were no significant differences in the levels of microdialysate glucose in either noninjured or pericontusional brain when the combined HBO2/NBH treatment and control groups were compared.

**Oxygen Toxicity**

The combined HBO2/NBH group’s levels of microdialysate glycerol were significantly decreased in comparison with those of the control group in both the noninjured and pericontusional brain (p < 0.001). The combined HBO2/NBH group’s levels of CSF F2-isoprostane were decreased by approximately 10% after treatment in comparison with the control group and this decrease almost reached statistical significance (p = 0.0692). The post-treatment BAL levels of IL-6 and IL-8 cytokines in the HBO2/NBH group did not significantly differ from levels in the control group.

One patient in the combined HBO2/NBH group had his treatment stopped as a result of increased baseline FiO2 requirements and chest radiograph changes. There was no increased incidence of pneumonia, FiO2 requirement of 50% or more, or PEEP > 10 cm H2O for the combined HBO2/NBH group as compared with the control group.

**Clinical Outcome**

One patient from the combined HBO2/NBH group and one patient from the control group were lost to follow-up at 6 months; therefore the 6-month outcomes are based on 19 patients in the combined HBO2/NBH group and 21 control patients, for a total of 40 patients.

The mortality rate was 16% for the combined HBO2/NBH group as compared with 42% for the control group. This 26% reduction (absolute percentage) in mortality for the combined HBO2/NBH group as compared with the control group was statistically significant (p = 0.0482).

The statistical analysis also showed that 8 (38%) of the 21 patients in the control group and 14 (74%) of the 19 patients in the combined HBO2/NBH group had a favorable outcome based on the sliding dichotomized GOS.
This difference represents an absolute 36% improvement in favorable outcome and is statistically significant (p = 0.0239). Based on the dichotomized GOS, 7 (33%) of 21 patients in the control group and 11 (58%) of the 19 patients in the combined HBO2/NBH group had a favorable outcome. This is a 25% absolute improvement, which almost reached statistical significance (p = 0.077).

Discussion

This is the first report on a prospective, randomized Phase II clinical trial combining HBO2 and NBH as a single treatment and comparing its effect in terms of surrogate markers of oxidative metabolism, ICP, and O2 toxicity as well as clinical outcome to results in a control group of patients treated with standard care. In addition, the effect of the treatment on cerebral metabolism was studied in both relatively noninjured brain and pericontusional brain tissue. The perilesional area or “traumatic penumbra” has biochemical signs of cerebral energy failure and cell membrane degradation with the capacity to regain a normal metabolic pattern. There is a significant difference between the energy metabolism of pericontusional tissue and that of relatively noninjured brain tissue in the same patients. Cerebral energy metabolism is severely decreased in the pericontusional area while being much closer to normal outside of this zone. Combined HBO2/NBH treatment appears effective in improving cerebral metabolism in both areas of the traumatically injured brain. In addition, the combination of HBO2 and NBH therapy appears to have increased therapeutic efficacy as compared with the 2 treatments in isolation.

Mechanism of HBO2

Hyperbaric O2 therapy appears to have several protective mechanisms of action in severe TBI, likely increasing its potential effectiveness. These mechanisms have been demonstrated in both experimental and clinical investigations and include improved oxidative metabolism and mitochondrial function and reductions in intracranial hypertension, apoptosis, neuroinflammation, and free radical–mediated damage. The results of the present randomized clinical trial help to support these findings.

Reduced cerebral blood flow is particularly critical in decreasing substrate delivery in the first 24 hours following severe TBI. Studies of cerebral blood flow have revealed a pericontusional zone of low blood flow, which often corresponds to the hypodensity seen on CT scans. In addition, diffusion barriers reduce cellular delivery of O2 following TBI and decrease the ability of the brain to increase O2 extraction in response to hypoperfusion. The phenomenon is particularly operative in pericontusional areas. Studies have shown that local brain tissue PO2 levels are significantly correlated with ischemia and outcome. Hyperbaric O2 therapy clearly leads to
a remarkable increase in the amount of $O_2$ delivered to relatively uninjured brain tissue in patients with TBI.\textsuperscript{45} The present study documents that $O_2$ delivery is also significantly increased to pericontusional areas under hyperbaric conditions.

Our previous investigations of HBO\textsubscript{2} in the treatment of severe TBI support the theory that the combination of HBO\textsubscript{2} and NBH therapy potentially has a synergistic effect.\textsuperscript{44,45} During those studies, markers of cerebral metabolic metabolism such as the cerebral metabolic rate of $O_2$, microdialysate lactate, and microdialysate $L/P$ ratio did not improve during the actual HBO\textsubscript{2} treatment but did improve during the next 6–24 hours following HBO\textsubscript{2} treatment. When the combined HBO\textsubscript{2}/NBH treatment paradigm was used, the markers for cerebral metabolism, ICP, and oxygen toxicity improved in-treatment, especially in the pericontusional brain. This improvement is likely secondary to the fact that the in-treatment measurements were taken 1 hour after the HBO\textsubscript{2} treatment, while the patients were still receiving NBH. The data suggest that HBO\textsubscript{2} enables the brain to use increased FiO\textsubscript{2} in the post-treatment period. Experimental investigations also support the concept of using HBO\textsubscript{2} followed by continued increased $O_2$ at normobaric pressures as a single treatment.\textsuperscript{9} Daugherty et al.\textsuperscript{9} in a lateral fluid percussion TBI rat model with 1 hour of HBO\textsubscript{2} treatment at 1.5 ATA followed by 3 hours of NBH, have documented significant improvement in mitochondrial function as measured by redox potential at the completion of the 4 hours of treatment but not at completion of 1 hour of HBO\textsubscript{2}. These data indicate that mitochondrial function is depressed after TBI but there is a potential for mitochondrial functional recovery and that the combination of HBO\textsubscript{2} and NBH can enhance this recovery. In addition, another experimental study, using the same treatment paradigm, showed that elevated brain tissue $O_2$ favorably influences the binding of $O_2$ in the mitochondrial redox enzyme system leading to significantly reduced cell loss in the CA2–3 region of the hippocampus and improved mitochondrial function and ATP production.\textsuperscript{65} A significant improvement in functional recovery as measured by a Morris water maze test also was shown. This effect was not seen in the NBH-treated or control animals.\textsuperscript{65} The results of these studies corroborate the findings that HBO\textsubscript{2} used in combination with NBH enhances cellular metabolism by increasing intracellular $O_2$ levels, thereby improving mitochondrial function, which results in enhanced $O_2$ utilization post-treatment.

Further experimental studies have found that HBO\textsubscript{2} restores the loss of the mitochondrial transmembrane potential and that the reduction of apoptotic cell death mediated by HBO\textsubscript{2} is achieved by a mitochondrial protective effect.\textsuperscript{39,50} The investigators theorize that the increased intracellular $O_2$ bioavailability resulting from HBO\textsubscript{2} may contribute to the preservation of mitochondrial integrity and reduce the activation of the mitochondrial pathway of apoptosis. Clinical trials have shown increased global $O_2$ consumption lasting for at least 6 hours after HBO\textsubscript{2} treatment.\textsuperscript{44,45} This increase appears to be secondary to improved mitochondrial function. In addition, the effect is seen for at least 5 days postinjury in human TBI patients treated with HBO\textsubscript{2}. Thus, HBO\textsubscript{2} improves oxidative metabolism during the period of prolonged posttrauma hypometabolism.

Experimental studies have shown that energy failure after trauma in the region of a contusion activates monovalent cation channels in penumbral capillary endothelial cells resulting in capillary fragmentation allowing extravasation of blood and progressive hemorrhage associated with worse clinical outcomes.\textsuperscript{48,49} Hyperbaric $O_2$ has decreased the size and the amount of brain destruction in a cerebral contusion rat model.\textsuperscript{50,51} The present study documents that with improved brain tissue $O_2$ delivery to pericontusional areas, markers of cerebral metabolism improve. Improved energy production would prevent the activation of monovalent cation channels in penumbra capillary endothelial cells, providing a mechanistic rationale for the observation that HBO\textsubscript{2} reduces the size of hemorrhagic contusions.

Acute inflammation in the perilesional area, while important to the repair process, contributes to secondary neuronal death.\textsuperscript{8,64} Neutrophils contribute to secondary injury by causing microvascular occlusion, releasing free $O_2$ radicals, proteolytic enzymes, and proinflammatory cytokines.\textsuperscript{8,25,59} Matrix metalloproteinases are a group of enzymes that have been demonstrated to be upregulated in experimental TBI. Neutrophils are the primary source of MMPs which, in turn, contribute to brain damage. The effect of HBO\textsubscript{2} on neuroinflammation and on the expression of MMP-9 was studied in a cortical contusion rat model.\textsuperscript{59} Neutrophils were revealed by myeloperoxidase staining, and immunohistochemical staining for MMP-9 was performed. The HBO\textsubscript{2}-treated group had a significant decrease in neutrophilic inflammatory infiltration compared with the control group. The expression of MMP-9 also was significantly lower in the HBO\textsubscript{2} group. These results demonstrated that HBO\textsubscript{2} decreased the extent of secondary cell death in reactive neuroinflammation in a cortical contusion TBI model compared with controls. Decline of MMP-9 expression after HBO\textsubscript{2} may also contribute to protection of brain tissue in the perilesional area.

Oxygen Toxicity

As in previous clinical trials performed at our institution,\textsuperscript{31,44,45} there were no signs of cerebral or pulmonary $O_2$ toxicity in the present trial. Brain tissue is especially vulnerable to lipid peroxidation because of its high rate of $O_2$ consumption and higher content of phospholipids.\textsuperscript{12,13,23} Cerebrospinal fluid F2-isoprostanes are a unique series of prostaglandin-like compounds formed in vivo from the free radical–catalyzed peroxidation of arachidonic acid and have been used to assess peroxidation in patients with severe TBI.\textsuperscript{3,4,17,35} Glycerol is an end product of phospholipid degradation in neural tissue cell membranes and is a marker of cell damage whether caused by $O_2$ toxicity via free radical formation and lipid peroxidation or secondarily from ischemia.\textsuperscript{16,19,33} Levels of CSF F2-isoprostanes as well as microdialysate glycerol were significantly decreased following combined HBO\textsubscript{2}/NBH treatment. These findings may not only signify that there were no signs of $O_2$ toxicity from the combined HBO\textsubscript{2}/NBH treatment, but, in
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fact, that there was a protective effect against neuroinflammation and free radical–mediated damage.

The lung is the organ most commonly damaged by hyperoxia, since O\textsubscript{2} tension in the surface area exposed to O\textsubscript{2} in the lungs is substantially higher than in other tissues.\textsuperscript{26} When the inhaled O\textsubscript{2} exceeds the protective capacity of antioxidants present in the lungs, acute pulmonary pneumonia is associated with the release of proinflammatory cytokines by alveolar macrophages, specifically IL-8 and IL-6, develops.\textsuperscript{40} The amount of these proinflammatory cytokines in the BAL is associated with acute lung injury and pulmonary infection similar to acute respiratory distress syndrome.\textsuperscript{42,43} In the combined HBO\textsubscript{2}/NBH group, patients’ BAL levels of IL-6 and IL-8 cytokines did not significantly differ posttreatment from the control group levels. Correspondingly, there was no increased incidence of pneumonia, FiO\textsubscript{2} requirements greater than 50%, or PEEP > 10 cm H\textsubscript{2}O compared with the control group.

**Intracranial Pressure**

Intracranial hypertension is the major cause of deterioration and death in the 1st week following severe TBI.\textsuperscript{24,39} Again, in this smaller trial, intracranial hypertension was significantly reduced by the combined HBO\textsubscript{2}/NBH treatment and that improvement continued until the next treatment session. The TIl score (used to assess the aggressiveness of intracranial hypertension) was correspondingly reduced.

**Clinical Outcome**

The clinical outcome of the combined HBO\textsubscript{2}/NBH treatment was significantly improved at 6 months compared with controls in this relatively small group of patients. There was an absolute 26% reduction in mortality, as well as a 36% improvement in favorable outcome using the sliding dichotomized GOS and a 25% improvement using the dichotomized GOS. This outcome is significantly better than our prior experience using HBO\textsubscript{2} as a single treatment or reports from the literature using NBH.\textsuperscript{44,41} This improvement in clinical outcome may be due to the synergistic effect of combining HBO\textsubscript{2} and NBH treatments. There was significant improvement in markers of cerebral metabolism and oxygen toxicity as well as ICP during the NBH portion of the combined HBO\textsubscript{2}/NBH treatment. The combined HBO\textsubscript{2}/NBH treatment also significantly improved markers of cerebral metabolism in pericontusional brain tissue as well as “normal” areas posttreatment for several hours as compared with values in the control group. Normobaric hyperoxia following an HBO\textsubscript{2} treatment increases the baseline O\textsubscript{2} available for mitochondria. The continued increased O\textsubscript{2} bioavailability enhances the effect of HBO\textsubscript{2} treatment. There have been several studies in the literature that show that improvement in markers of cerebral metabolism and ICP correlate with clinical outcome.\textsuperscript{14,24,27,33,34,40,47,55}

In addition to improving cerebral metabolism and ICP, the combined HBO\textsubscript{2}/NBH treatment significantly improved markers of cerebral oxygen toxicity. It is possible that the increased intracellular O\textsubscript{2} bioavailability resulting from the combined HBO\textsubscript{2}/NBH treatment may result in the neuroprotection of mitochondrial integrity and reduce the activation of the mitochondrial pathway of apoptosis, and the treatment may reduce free radical–mediated damage as shown in experimental studies.\textsuperscript{38,39,50-61} This neuroprotective action of the combined HBO\textsubscript{2}/NBH treatment could lead to the preservation of viable but nonfunctioning mitochondria, which would in turn improve clinical outcome.

A major limitation of the clinical outcome portion of this study is the relatively small number of patients. This trial was not designed or powered to be an outcome study, as the primary focus was on cerebral metabolism, ICP, and oxygen toxicity. Therefore, the outcome results need to be interpreted with caution. However, they point toward the need for a Phase III trial to determine if the combined HBO\textsubscript{2}/NBH treatment could become a significant treatment for patients suffering a severe TBI.

**Statistical Methods**

Mixed-effects models, such as those used here and accomplished using the restricted maximum likelihood technique, are highly recommended for analyses in which data are obtained repeatedly but not necessarily at regular or identical times from a cohort of study participants.\textsuperscript{56} Vespa et al.\textsuperscript{56} have stated that mixed-effects models should be used by all researchers studying interdependent serial physiological data. The mixed-effects model controls for the interrelatedness of sequential hourly values within each patient. These models take into account the differences in group sizes and correct for differences in pretreatment values (such as the difference in BAL IL-8 levels) in the calculation of significance.

**Generalizability of the Treatment Protocol**

Safe treatment of severe TBI patients with HBO\textsubscript{2} requires institutional expertise in the management of severe TBI as well as in critical care hyperbaric medicine.\textsuperscript{21,42} The HBO\textsubscript{2} chamber and its environment must become an extension of the ICU to allow safe care of the patient with severe TBI. The expertise of appropriate personnel must be as readily available in the HBO\textsubscript{2} environment as it is in the ICU. A monoplace chamber has a relatively small physical space footprint and can be incorporated in or placed adjacent to a critical care support area.\textsuperscript{45} The delivery of HBO\textsubscript{2} treatments is relatively labor intensive. It requires transport of the patient to and from the chamber, and proximity of the HBO\textsubscript{2} chamber to the ICU minimizes transportation time. Monitoring of the ventilatory status of the patient with severe TBI during transport is critical and includes pulse oximetry and portable end-tidal CO\textsubscript{2} monitoring. The monoplace chamber has to be specifically designed to adequately monitor the patient and administer appropriate fluids and medications during the treatment.\textsuperscript{21} Intermittent HBO\textsubscript{2} treatments at 1.5 ATA for 60 minutes have resulted in a very low incidence of complications, all of which were reversible. When a monoplace chamber is used, the patient is physically isolated from health care providers, but the chamber can be decompressed in approximately 2 minutes and rapid access to the patient achieved. Our institution has delivered 1984

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HBO2 treatments in 3 prospective clinical studies, and an emergency decompression has never been required.41,44,45 If a proper treatment paradigm is maintained, our experience documents that HBO2 treatment can be safely delivered to patients with severe TBI in monoplace as well as multiplace chambers.

Blast Injuries and HBO2

Blast injuries to the brain represent a spectrum of severity similar to traditional TBI. Armonda and other investigators have documented that the severe injuries are characterized by edema, vasospasm, and intracranial hemorrhage.1,2 In severe cases the onset of edema has been rapid and life threatening, requiring emergent decompressive craniectomy. Vasospasm of the internal carotid and anterior cerebral arteries is frequently related to intracranial hemorrhage resulting from penetrating fragments. To the authors’ knowledge, no investigations using HBO2 have been applied to this type of injury. However, the HBO2 neuroprotective mechanisms discussed earlier in preclinical and clinical investigations of severe TBI could well be beneficial to patients with explosive blast brain injuries. There have been investigations of HBO2 therapy for blast-induced postconcussion syndrome and posttraumatic stress disorder.22 The patients experienced their injuries at least 12 months prior to HBO2 treatment. The preliminary report by Harch et al.22 suggests that HBO2 should be studied in a larger catchment of patients. The mechanism of action of HBO2 in this setting has not been clearly delineated. It is hypothesized that the potential improvement in neurological function relates to improved cerebral blood flow, particularly to the hippocampus.2,63

In summary, the treatment of blast-induced TBI with HBO2 is at a preliminary stage but deserves further investigation.

Conclusions

Data in this study can be summarized by the following key points: 1) The combined HBO2/NBH treatment significantly improved markers of oxidative cerebral metabolism in relatively uninjured brain tissue but, importantly, also in pericontusional tissue. 2) The combined HBO2/NBH treatment reduced intracranial hypertension and thereby decreased the therapeutic intensity of treatment of intracranial hypertension. 3) There was no evidence of O2 toxicity either in the brain or lungs, and there was actual demonstrated improvement in markers of cerebral toxicity. 4) Combining HBO2 and NBH into a single treatment potentially has a synergistic therapeutic effect. 5) The combined HBO2/NBH treatment reduced mortality and improved favorable outcome as measured by the GOS at 6 months. This improvement was significantly better than past clinical outcomes observed with either of the treatments used separately. The clinical outcome portion of this study is limited by a relatively small number of patients.

Disclosure

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