Hyperbaric oxygen treatment in children: experience in 329 patients

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Abstract
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Introduction: Paediatric patients, like adults, may undergo hyperbaric oxygen treatment (HBOT) in both life-threatening situations and chronic diseases. There are particular challenges associated with managing paediatric patients for HBOT. This paper documents the indications, results, complications, and difficulties that occur during HBOT for a large cohort of paediatric patients and compares them with adult data in the literature. Methods used to reduce these difficulties and complications in children are also discussed.
Methods: This was a 15-year retrospective review of paediatric patients treated with HBOT at two hyperbaric centres. Between January 2006 and June 2021, patients under the age of 18 who received at least one session of HBOT were included.
Results: Three hundred and twenty-nine paediatric patients underwent a total of 3,164 HBOT exposures. Two-hundred and fifty-four patients (77.2%) completed treatment as planned and 218 (66.5%) achieved treatment goals without complications. Two patients treated for carbon monoxide poisoning exhibited neurological sequelae. Amputation was performed in one patient with limb ischaemia. Middle ear barotrauma events occurred in five treatments. No central nervous system oxygen toxicity was recorded during the treatments.
Conclusions: This patient series indicates that HBOT can be safely performed in pediatric patients with low complication rates by taking appropriate precautions. The cooperation of hyperbaric medicine physicians and other physicians related to paediatric healthcare is important in order for more patients to benefit from this treatment. When managing intubated patients an anaesthesiologist may need to participate in the treatment in order to perform necessary interventions.

Introduction

According to the Undersea and Hyperbaric Medical Society (UHMS), hyperbaric oxygen treatment (HBOT) is a medical treatment based on breathing 100% oxygen in hyperbaric chambers at pressures higher than 101.3 kPa (1 atmosphere absolute pressure [atm abs]) although the inspired pressure of oxygen should be at least 142 kPa (1.4 atm abs) or more for clinical effect.[1] Treatment is performed in monoplace or multiplace hyperbaric chambers at pressures (in most indications) between 203 to 284 kPa (2.0 to 2.8 atm abs) for 90–120 minutes. Oxygen is inhaled through a mask, hood or endotracheal tube or from ambient air if the chamber is pressurised with 100% oxygen. The physical, physiological and biochemical effects of hyperbaric oxygen are described elsewhere.[2–6] Indications for HBOT are determined by the UHMS and the European Committee of Hyperbaric Medicine (ECHM), and consensus reports with evidence levels are published.[1,7] Hyperbaric oxygen treatment in Turkey is administered for indications determined by the Ministry of Health in association with these reports. These indications have been included in the reimbursement list by the Social Security Institution.[8] While HBOT is the primary treatment for decompression sickness and arterial gas embolism, it is used as adjunctive treatment in carbon monoxide (CO) and cyanide poisoning, necrotizing soft tissue infections, necrotising fasciitis, clostridial myonecrosis (gas gangrene), crush injury, compartment syndrome and other acute traumatic ischaemias, diabetic and non-diabetic chronic ulcers, thermal burns, radiation injuries, chronic refractory osteomyelitis, sudden visual and hearing loss, femoral head necrosis and some type of intracranial abscesses.[1,7–9] The number of daily sessions is determined according to the disease. The most common side effects observed in treatment are barotraumas due to raised pressure.[10]

Currently, there are a total of 54 centres providing HBOT in general hospitals and independent centres in Turkey (53 multiplace facilities, and one monoplace chamber facility). However, there are no hyperbaric chambers in any paediatric hospitals. Due to the unique needs of the paediatric age group and the potential high risk of inter-hospital transfers, especially for intensive care patients, there may be delays in treatment. There is a lack of studies in the literature on the problems encountered during HBOT in children.

This study aimed to document the indications for HBOT among paediatric patients in Turkey, and to appraise treatment results, problems (such as ear equalisation problems and anxiety), and other adverse events. A further goal was to discuss strategies to minimise difficulties and adverse events in children.

Methods

Approval for this retrospective study was obtained from the Ethics Committee of İzmir Tepecik Education and Training Hospital (2021/05-15). Files and system records were searched for paediatric patients (0 to 18 years of age) who received HBOT between 1 January 2006 and 15 May 2021. Demographic data, indications, HBOT protocol and number of sessions, problems encountered during the treatments, complications, and treatment outcomes were extracted.

Hyperbaric oxygen treatments were performed in multiplace hyperbaric chambers (Barotech, Turkey) and in sessions of 90–120 min at 203–304 kPa (2–3 atm abs). Informed consent was obtained from the parents before the treatment. HBO staff accompanied all children throughout the treatments. In elective cases, we showed the children the hyperbaric chamber before treatment, introduced them to the staff and explained all aspects of the treatment. Children under the age of four underwent treatment together with family member inside the chamber. In addition, we allowed children with anxiety symptoms (who did not want to enter the hyperbaric chamber alone, were afraid, cried and refused treatment) to attend the first session with a family member. Family members who were taken to the hyperbaric chamber with the patient where necessary, were also examined before hyperbaric exposure and chest X-rays were taken. However, X-rays were not ordered in life-threatening emergencies.

Since CO poisoning usually affects other family members many of our paediatric patients were treated together with their families. We allowed them to take toys that do not pose a fire hazard as a distraction during compression. There are two monitors in the hyperbaric chambers, and patients can watch movies on these monitors during treatment. In order to make the treatment more enjoyable for paediatric patients, we turned on their favorite, age-appropriate animations or cartoons. We taught the children ear equalisation manoeuvres before the treatment, with those who failed to perform such manoeuvres to stretch or chew gum. For younger children we allowed them to suck a bottle. Patients who could not adapt to an oxygen delivery mask, very young children and infants breathed oxygen through a hood. Intubated patients were ventilated using a pneumatic ventilator. The endotracheal tube cuff was filled with liquid instead of air to prevent changes in cuff volume during changes in ambient pressure.

During the treatments, patients were monitored through portholes and cameras, and verbal communication was provided via intercom. We used the chamber medical lock for drugs and small equipment required during the treatment and the entry lock of the hyperbaric chamber for larger medical equipment, patient or physician entrances and exits. Our hyperbaric chambers have a fire extinguishing system against the risk of fire. In addition, while no electrical devices were taken into the chamber, the oxygen level inside was closely monitored throughout the treatments and the chamber was ventilated as needed. During the treatment, the temperature was controlled with a specially designed air conditioning system.

Data were entered into a Microsoft Excel (Microsoft®, US) spreadsheet under the categories of: complete healing, minor morbidity (partial improvement in hearing loss, minor amputation, skin grafting or surgical debridement), major morbidity (no improvement in hearing loss, major debridement/amputation and neurologic sequelae), death, and complications related to HBOT. These data were subject to statistical analysis with Microsoft 365 Excel 2021.

Results

PATIENTS AND CONDITIONS TREATED

During a 15-year period, we treated a total of 329 patients aged 0–18 years with eight indications in two HBOT centres (Table 1). We performed a total of 3,164 patient sessions in 329 patients (mean treatments per patient 9.6, standard deviation [SD] 12.6, 95% confidence interval [CI] 4.2–15.1). Two hundred and fifty four patients (77.2%) completed their treatment as planned. Forty-eight patients (14.6%) terminated their treatment voluntarily. In three patients (0.9%), treatment was discontinued due to a different treatment plan of the responsible physician. We could not obtain information about the treatment outcome of 24 patients (7.3%). No patient discontinued treatment due to claustrophobia.

The mean age was 12 years (range 0.75–18). The first session in treatment of carbon monoxide poisoning and necrotising anaerobic soft tissue infections lasted for 90 min at 284 kPa (2.8 atm abs) using a protocol incorporating three 25-minute oxygen periods separated by five-minute air breaks, and for other indications lasted 120 min at 243 kPa (2.4 atm abs) using a protocol incorporating three 30-minute oxygen periods again separated by five-minute air breaks. Ninety-six patients (29.2%) underwent treatment with family members; 36 were treated together because they were younger than four years old, and 60 patients because their families also had CO poisoning. Thirty-seven patients breathed oxygen through a hood. Six patients were treated while still receiving ventilation support.

We treated a total of 234 (71.1%) paediatric patients with CO poisoning aged between nine months and 18 years (30.3% of total sessions). The source of CO was gas leaking from a stove (wood or coal) in 176 patients (75.2%) and a water heater in the bathroom in 46 patients (19.7%). Four patients (1.7%) were poisoned by trying to warm up with a barbecue

Table 1
Indication, patient demographics and number of sessions for 329 children treated with HBOT; F – female; M – male; SD – standard deviation

Indication	*n*	Mean (SD) age	Sex (F:M)	Mean (SD) sessions
Carbon monoxide poisoning	234	12 (4.7)	135:99	4.1
Sudden hearing loss	37	16 (2.7)	19:18	15.6
Delayed wound healing	23	11 (4.3)	12:11	28.3
Chronic refractory osteomyelitis	17	15 (4.4)	10:7	29.4
Crush injury, compartment syndrome	8	14 (4.3)	2:6	20.5
Femoral head necrosis	4	12 (2.5)	2:2	40.3
Soft tissue radionecrosis	4	14.5 (5.9)	3:1	28.5
Central retinal artery occlusion	2	12 (2.8)	1:1	20.0
Total	329	12 (4.7)	184:145	9.6 (12.6)

Table 2
Treatment outcomes by indication in 329 children treated with HBOT; CO – carbon monoxide

Indication	*n*	Complete recovery	Recovery with minor morbidity	Recovery with major morbidity	No recovery	Complication	Withdrawal from treatment
CO poisoning	234	189	2	2	1	1	39
Sudden hearing loss	37	4	8	0	13	1	11
Delayed wound healing	23	13	0	0	2	0	8
Chronic refractory osteomyelitis	17	5	0	0	4	1	7
Crush injury, compartment syndrome	8	4	1	0	0	1	2
Femoral head necrosis	4	2	1	0	1	0	0
Soft tissue radionecrosis	4	1	0	0	1	1	1
Central retinal artery occlusion	2	0	2	0	0	0	0
n (%)	329	218 (66.3)	14 (4.2)	2 (0.6)	22 (6.7)	5 (1.5)	68 (20.7)

indoors, two patients (0.9%) by smoke inhalation in a fire, two patients (0.9%) by a liquefied petroleum gas (LPG) stove in the kitchen, two patients (0.9%) by hookah smoking, one patient (0.4%) by natural gas and one patient (0.4%) by LPG as a result of suicide attempt. In all cases, poisoning occurred at home. The most common symptom was change in consciousness and transient loss of consciousness (81.2%) followed by headache (63.7%). Nausea and vomiting were present in 44% and balance disturbance in 21.8%. Carboxyhaemoglobin (COHb) levels were measured in 185 patients at presentation and 151 had COHb levels > 20%. However, we did not observe any clinical correlation between COHb level and severity of symptoms. One hundred and eighteen patients were poisoned together with family members (35.9%). The total number of HBOT sessions administered among the 234 CO poisoning patients was 959.

We treated 37 patients (11.3%) with sudden hearing loss. In six the hearing loss was total, and in two cases there was bilateral involvement. We administered an average of 15.6

Table 3
Adverse events by indication in 329 children treated with HBOT

Indication	Ear barotrauma	Anxiety
Carbon monoxide poisoning	1	49
Sudden hearing loss	1	0
Delayed wound healing	0	5
Chronic refractory osteomyelitis	1	3
Crush injury, compartment syndrome	1	1
Soft tissue radionecrosis	1	1
Total	5	59

HBOT sessions to each patient; 18.2% of sessions were administered for this indication.

We treated a total of 23 patients (7.2%) for delayed wound healing (surgical wounds, chronic ulcers of the skin, ulcers on deformed feet due to meningomyelocele and necrotising soft tissue infections). The average number of sessions was 28.3; 20.5% of all sessions were administered for this condition.

Seventeen patients were treated with the diagnosis of chronic refractory osteomyelitis and the average number of sessions was 29.3 (15.8% of all sessions). Nine patients had femur osteomyelitis, seven patients had tibia-fibula osteomyelitis and one patient had humeral osteomyelitis. Eleven developed after traffic accidents. Four developed as a result of other trauma, and two developed as a result of septic arthritis.

We treated eight patients with the diagnosis of crush injury and compartment syndrome (2.4%). We administered a mean number of 20.5 sessions of HBOT (5.2% of all sessions). We applied 5.3% of all sessions to four patients (1.2%) whom we treated for femoral head necrosis. Four patients (1.2%) were treated with the diagnosis of soft tissue radionecrosis. Three of the patients had radiation cystitis and one had radiation myelitis (3.6% of all sessions).

We treated two patients (ages 12 and 14) with unilateral central retinal artery occlusion and administered 20 sessions of HBOT each (1.3% of all sessions).

TREATMENT RESULTS

Treatment results are shown by indication for HBOT in Table 2. We achieved complete recovery in 66.3% of patients (n = 218). As a result of CO intoxication, two patients recovered with major morbidity (neurological sequelae) (0.6%) and 14 patients recovered with minor morbidity (4.3%). In 22 patients (6.7%), there was no improvement.

OUTCOMES AND ADVERSE EVENTS

A total of 64 adverse events were observed in 3,164 treatment sessions (2% of the 3,164 patient treatments) (Table 3). Fifty-nine of these events (1.9% of patient treatments) were anxiety experienced by children in the hyperbaric chamber. There were no patients who refused treatment due to claustrophobia. Only five of the 329 patients (1.5%) had a single episode of ear barotrauma, which is only 0.2% of the 3,164 treatment sessions. There was no resulting morbidity or disability in these patients. An otolaryngologist performed a prophylactic myringotomy before treatment in one patient presenting with a middle ear ventilation disorder. We also did not encounter any central nervous system (CNS) or pulmonary oxygen toxicity in either children or family members accompanying them during treatment. Six patients (1.9%) were treated while still receiving ventilation support in the hyperbaric chamber and were accompanied by an anaesthesiologist. These patients did not develop any complications requiring intervention during the treatments. A total of 241 patients including six intubated patients were transported to our clinics via ambulance. We did not record any complications during patient transport to the HBOT centre.

Discussion

The indications for HBOT have been determined by international organisations, with the indications and levels of evidence updated via consensus meetings.[1,7] All patients we treated presented with indications accepted in the consensus reports published by the UHMS. Since there are no randomised controlled trials of HBOT in any of its accepted indications in paediatric patients, the same indications as for adults are also used for children.[11–13] The only study published in Turkey on HBOT in children is a thesis study in which paediatric patients treated at Istanbul University over 30 years were evaluated.[14]

In the present study, the most common disease treated was CO poisoning (71.1%) which was similar to the 79% of CO poisoning reported in another series of 139 paediatric patients.[12] Carbon monoxide is one of the leading fatal toxins globally typically occurring as a result of incomplete combustion of carbon-containing materials; it is not uncommon in children.[15–17] Complete resolution occurred with a single HBO session in 87 patients and the treatment was terminated. One hundred forty-seven patients required more than one treatment. Two patients who recovered with neurologic sequelae were also intubated before HBOT. The mean number of HBO sessions given was 4.1 and none of our patients presented with late sequelae. Similarly, no late neuropsychiatric sequelae were reported in another series of 111 patients.[12]

Sudden sensorineural hearing loss occurs with a mean loss of 30 dB or more in at least three consecutive frequencies. It

is a rare condition in the paediatric age group and there are very few relevant studies in the literature.[18] In adults, HBOT is recommended to be used in combination with medical treatment.[7,19] We did not find any published cases of sudden hearing loss treated with HBOT in children. However, it was the second most treated indication in the present. This may be explained, at least locally, by the increasing use of HBOT in sudden hearing loss and the awareness of ENT physicians about HBOT.[18,19]

The 23 patients treated for delayed wound healing accounted for 20.5% of the sessions performed (7.2% of the patients). In this group, adherence to treatment was quite high and the rate of patient discontinuation was low. This can be explained by adequate wound care in our clinics. In contrast to other studies,[20,21] necrotising soft tissue infections were very rare in our cohort. We did not have any paediatric patients presenting with necrotising fasciitis or gas gangrene. Relevant presentations were mostly from orthopedic clinics and patients with wound healing problems at the operation site. Three children with necrotising soft tissue infections were given HBOT after surgical intervention for anaerobic crepitant cellulitis and parenteral antibiotics. We treated the patients with two sessions per day at 284 (2.8 atm abs) on the first day and one session per day at 243 kPa (2.4 atm abs) thereafter.

Hyperbaric oxygen reduces tissue hypoxia and necrosis with its anti-hypoxic effect in crush injuries, compartment syndrome and other acute traumatic ischemias;[22] it also reduces tissue oedema with its vasoconstrictive effect. Hyperoxia increases the phagocytosis and bacterial killing ability of leukocytes.[23] In this study, minor amputation was performed in one patient with crush injury. Various levels of amputation were reported in other paediatric patient series.[12,13,20]

Adverse events that occur in HBOT are typically pressure-related events (ear barotrauma, sinus barotrauma), and hyperoxia-related events (visual refractive changes, pulmonary oxygen toxicity, central nervous system toxicity) and claustrophobia. The overall rate of adverse events was quite low in the present series compared with with other paediatric patient series in the literature. For example, one study reported a 5.3% adverse event rate,[13] and another reported a total of 47 adverse events including hypotension, bronchospasm, haemotympanum, and hypoxemia in a series of 32 critically ill patients.[21] The most common adverse event in HBOT is middle ear barotrauma. In adult patients, the incidence of barotrauma is reported at very variable rates in different series.[24–30] One study reported 1.9% ear barotrauma in 11,142 patient sessions,[25] while in another the rate of barotrauma was 3.05% and symptoms occurred mostly in the first three sessions.[27] In a third adult series the overall adverse event rate was 17.4% and the main complication was middle ear barotrauma which occurred in 9.2% of patients and 0.04% of sessions.[31] In this paediatric series, ear barotrauma was detected in 1.5% of patients and 0.15% of sessions. There are several reasons why ear barotrauma seemed rare. First, we examined the patients before accepting them for treatment, and assessed their risk of barotrauma. We also evaluated the patients before each session and interrupted the treatment in cases where there was an elevated risk of barotrauma, such as during inflammatory diseases of the upper respiratory tract. The presence of HBOT staff in the sessions and the fact that children under the age of four were taken into the hyperbaric chamber with their parents in the first session may also have contributed to the low incidence of adverse events in general. In addition, we kept the compression rate in the range of 10 to 14 kPa·min^{-1} because of the higher risk of barotrauma in the first sessions.[24] However, we paid attention to the compression rate because very slow compression can also lead to barotraumas.[30] During the compression phase, HBO staff maintained eye contact with the children, which allowed us to intervene early in ear equalisation difficulties. Another potential reason for the low rate of barotrauma is that we taught patients different methods for ear equalisation before treatment and told children to choose whichever method provided easy equalisation. Children can learn the Valsalva and Frenzel manoeuvres or other Eustachian tube stretching movements such as yawning, swallowing, and chewing gum only at the age of 4–6 years. In younger children, sucking a bottle can open the Eustachian tube with a manoeuvre like the Frenzel. Nevertheless, myringotomy may be necessary before entering the hyperbaric chamber. Distractions during compression (such as safe toys for the hyperbaric chamber or TV) also facilitated ear equalisation. Children under four years of age attending their first session with a family member also helped to reduce complications.

It must also be acknowledged that signs of tympanic barotrauma were not prospectively evaluated using otoscopy among our patients, and had this been done it would almost certainly have resulted in a higher reported incidence of barotrauma.

Sinus barotrauma is the second most common barotrauma encountered in HBOT. The reported incidence in adults ranges from 1.2% to one in 10,000 treatments.[25,28] The incidence of pulmonary barotrauma is extremely low in routine HBO treatment sessions. The risk is reduced by performing chest radiography before treatment and evaluating patients in terms of contraindications and taking necessary precautions. There were no cases of sinus barotrauma or pulmonary barotrauma in our paediatric series.

A potentially serious side effects of high oxygen pressure is CNS oxygen toxicity. Its incidence is given at different rates in the literature (one in 2,000–10,000 patient sessions).[28,32] Pulmonary oxygen toxicity is usually not observed in routine HBO sessions. However, it may occur in a longer treatment such as the US Navy Treatment Table 6 used for

decompression illness.[28] There are no controlled studies suggesting that oxygen toxicity is more frequent in children than in adults. Oxygen toxicity has been reported at low rates in other paediatric patient series.[13,20] One study reported two cases of oxygen toxicity, one pulmonary and one CNS, but the incidence could not be determined because the total number of sessions was not reported.[12]

Hyperoxic myopia is a very common side effect in HBO treatments. The incidence has been reported between 25–100% in different adult patient series.[28,33] Interestingly, it is more pronounced when a hood oxygen delivery system is used compared to an oronasal mask.[34] Vision typically returns to normal 4–6 weeks after the end of treatment. Cataract is not expected in limited duration treatments. However, HBOT has occasionally been associated with faster progression of existing cataracts.[28,33] No ocular adverse events were observed in paediatric patients in the present study.

Claustrophobia is a condition with a rate of 2% in the general patient population and may cause confinement anxiety even in multiplace hyperbaric chambers.[28] Although confinement anxiety has been reported as 8 per 10,000 in different studies, it is actually thought to be higher.[24,33] In one study the rate was reported as 4.3%.[25] In paediatric patients, the rate of anxiety has been reported as 2–3.2%.[13,20] Confinement anxiety was the most common adverse event observed in the present study. Some HBOT centers, particularly in the USA, do not allow family members to go inside the chamber during the treatment. However, it is anxiety-inducing for a child to be in a closed room for two hours breathing oxygen through a mask, which they have never seen in their life. Therefore, we showed the children the hyperbaric chamber before the first treatment and explained what they would experience there. We introduced them to the hyperbaric personnel and allowed patients with anxiety symptoms to enter the hyperbaric chamber with their families. We also asked them to bring their toys that did not pose a fire risk in the hyperbaric chamber. We asked them about their favorite animated movies and cartoons and showed them those movies during the treatment. We allowed babies to suck a bottle in the chamber. Thanks to all these actions, confinement anxiety in children was minimised and adaptation to treatment increased.

Different sizes of laryngoscope sets, masks, and hoods should be available in the clinic. It is important that the HBO personnel who will accompany the patient are especially knowledgeable about critical patient management. Intubated patients should be accompanied by an anaesthesiologist during treatment. In addition, the mechanical ventilator should be set at appropriate values to avoid pulmonary barotrauma in paediatric patients.

It is acknowledged that one important limitation of this study is missing data regarding patients who terminated their treatment plans early.

Conclusions

Hyperbaric oxygen treatment can be life or limb saving in children.

Barotraumas, which are the most common adverse events among adults undergoing HBOT, can be reduced by teaching children different manoeuvres beforehand and through HBOT staff support in the hyperbaric chamber. Anxiety of confinement can be minimised by allowing family members to enter the hyperbaric chamber and allowing children to get to know the hyperbaric chamber and take appropriate toys with them before treatment. According to these observational data, HBOT can be used as a safe treatment with a low risk of adverse events in paediatric patients. Paediatric and intensive care physicians who follow the patient should be informed about the safety of HBOT. Critically ill patients can be safely transported in the presence of anaesthesiologists. In this way, more critically ill paediatric patients with appropriate indications can benefit from this treatment.

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