Physicians and critical care in hyperbaric chambers

Papers from the European Underwater and Baromedical Society (EUBS) special session at the 40th Annual Scientific Meeting in Wiesbaden, Germany, September 2014

The following four papers are based on previously unpublished presentations and discussions from the European Committee for Hyperbaric Medicine (ECHM) satellite symposium, Sharm El-Sheik, Egypt, in 2007 and updated at a special session of the EUBS Annual Scientific Meeting, Wiesbaden, September 2014. The session was co-chaired by Michael A Lang, OxyHeal Health Group, National City, California, USA, Karin Hasmiller, BG-Unfallklinik Murnau, Murnau-am-Staffelsee, Germany and Peter HJ Müller, Universitätsspital Basel, Basel, Switzerland and past European Editor, *Diving and Hyperbaric Medicine*.

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Hyperbaric oxygen therapy for intensive care patients: position statement by the European Committee for Hyperbaric Medicine

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Abstract

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Many of the accepted indications for hyperbaric oxygen treatment (HBOT) may occur in critically ill patients. HBOT itself may cause a number of physiological changes which may further compromise the patient's state. Guidelines on the management of critically ill patients in a hyperbaric facility have been founded on the conclusions of the 2007 European Committee for Hyperbaric Medicine (ECHM) meeting. With regard to patient management, HBOT should be included in the overall care of ICU patients only after a risk/benefit assessment related to the specifics of both the hyperbaric centre and the patient's clinical condition and should not delay or interrupt their overall management. Neither patient monitoring nor treatment should be altered or stopped due to HBOT, and any HBOT effects must be strictly evaluated and appropriately mitigated. With regard to the hyperbaric facility itself, the hyperbaric chamber should be specifically designed for ICU patients and should be fully equipped to allow continuation of patient monitoring and treatment. The hyperbaric chamber ideally should be located in, or around the immediate vicinity of the ICU, and be run by a sufficiently large and well-trained team of physicians, nurses, chamber operators and technicians. All devices to be introduced into the chamber should be evaluated, tested and acknowledged as safe for use in a hyperbaric environment and all procedures (standard and emergency) should be tested and written before being implemented.

Key words

Hyperbaric oxygen treatment, intensive care medicine, standards, ECHM - European Committee for Hyperbaric Medicine, safety, hyperbaric facilities, patient monitoring, ventilators, training

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Introduction

Hyperbaric oxygen treatment (HBOT) is a therapeutic modality in which oxygen (O_2) is given via the patient's respiratory system at a pressure above atmospheric pressure. The objective is to obtain an increase in tissue oxygen pressure, either to compensate for a deficiency in oxygen supply, or to recruit the effects of oxygen delivered at partial pressures above normal.

Many of the accepted indications for HBOT may occur in critically ill patients. However, HBOT causes many physiological changes that may further compromise a patient's haemodynamic and respiratory state. Furthermore, to provide intensive care inside a hyperbaric chamber is not an easy task and many hyperbaric centres do not have the chamber, equipment and trained staff to provide such care. Finally, the hyperbaric facility is rarely in the immediate vicinity of the intensive care unit (ICU), so repeated patient transport between the ICU and the chamber may be necessary, with all its attendant, potentially adverse events.

Therefore, the decision to treat an ICU patient with HBOT is made by a careful risk/benefit analysis related to the specifics

of both the hyperbaric centre and the patient's condition. This explains the heterogeneity in practice between centres that have developed an expertise in treating ICU patients and those more orientated towards outpatient treatment.

HBOT actions and indications in ICU patients

The therapeutic mechanisms of HBOT are complex and may be summarized as follows:[1,2]

- Reduction of the volume of gas bubbles by increasing the hydrostatic pressure;
- Correction of tissue hypoxia by increasing blood oxygen content via dissolved oxygen;
- Redistribution of blood flow to hypoxic areas due to reduction in oedema and the hyperoxic vasoconstriction in healthy regions, without inducing downstream hypoxia;
- Increased red blood cell deformability which, combined with the reduced oedema formation, enhances microcirculatory blood flow;
- Antibacterial actions through direct effects on anaerobic bacteria and indirect effects on aerobic bacteria by enhancing the microbiocidal capability of polymorphonuclear leukocytes;
- Enhanced cellular metabolism, with preservation of intracellular ATP and reduced oxidative injury to cells;
- Through actions on reactive oxygen and nitrogen species, the adherence properties of neutrophils are enhanced, modulating inflammatory cytokine production and enhancing protective tissue defence mechanisms such as heme oxygenase 1, heat shock proteins and hypoxia-inducible factor 1-χproduction.

These actions, alone or in combination, provide the rationale for HBOT. In the list of ECHM-accepted indications for HBOT, several may concern critically ill patients:

- Air or gas embolism;
- Decompression injury (especially severe neurological cases);
- Carbon monoxide poisoning (including that associated with burns, smoke inhalation or cyanide poisoning);
- Necrotising soft-tissue infections, including gas gangrene;
- Crush injury, compartment syndrome, open fracture Gustillo III b and c and other traumatic acute ischaemia;
- Selected cases of neurological disorders such as intracranial abscess;
- Compromised grafts and flaps in the immediate post-operative period;
- Acute burn injury.

Not all patients with such disorders are critically ill; it is often the most severe forms that require intensive care. All these disorders are accepted indications in Europe for HBOT currently treated in hyperbaric centres in hospitalized patients in a general ward or as an outpatient. However, if the patient requires ICU care, many hyperbaric physicians are reluctant to treat with HBOT, yet paradoxically it is these severely ill patients who may have the most to gain from the addition of HBOT to their clinical management.[3]

Physiological changes induced by HBOT

This reluctance to treat ICU patients with HBOT is explained in part by the fact that, besides the usual risks of HBOT (barotrauma, oxygen toxicity, claustrophobia, fire), HBOT induces several physiological changes that may further compromise the patient's condition, especially the cardio-respiratory systems.

VENTILATION

Two main factors have to be taken into account to predict patient respiratory behaviour under HBOT. Firstly for a patient breathing spontaneously, the increase in gas density induces an increase in airway resistance which, in turn, leads to an increase in the work of breathing and in respiratory muscle oxygen consumption. The patient must be monitored carefully and assisted/controlled ventilation may need to be introduced earlier than at normal atmospheric pressure. Because assisted modes of ventilation are often based on demand regulators, the effort required to trigger inspiration and the level of pressure support have to be taken into account in considering the extra work of breathing due to the hyperbaric environment.

Secondly because of the difficulties in setting up many ventilators correctly under hyperbaric conditions and the lack of an assisted mode of ventilation in some models, fully controlled ventilation is often the preferred mode in a hyperbaric chamber. This is not without consequences, as sedation is often required to avoid patient/ventilator asynchrony and to reduce the risk of barotrauma.

Ventilation with pure oxygen induces a decrease in mucociliary clearance and the development of pulmonary micro-atelectasis, increasing intrapulmonary shunt. Hypoxic episodes after HBOT sessions have been reported and are probably explained by these mechanisms.[4] In clinical practice, some simple measures may limit these problems; inhaled oxygen must be correctly humidified, a low level of positive end expiratory pressure (PEEP) should be applied (5–10 cm H_20) and if hypoxia occurs after the HBOT session, recruitment manoeuvres should be used.

HAEMODYNAMICS

Haemodynamics are influenced by the same two factors as ventilation. The increase in gas density induces an increase in intrathoracic pressure, leading to an increase in right ventricular afterload and a decrease in right ventricular venous return. Thus, the right ventricle is at risk of failure. Usually, moderate intravenous volume infusion (0.5–1.0 L) is required at the beginning of the HBOT session and is sufficient to correct hypotension. However, in some patients, vasoactive drug support may be required.

The hyperoxia induced during HBOT leads to arterial vasoconstriction and an increase in systemic vascular resistance and left ventricular afterload, so the left ventricle is also at risk of failure. At best, haemodynamics should be stabilized before the HBOT session. In the case of haemodynamic instability, extensive invasive haemodynamic monitoring may be required to guide volume infusion and inotropic support. Conversely, HBOT may stabilise haemodynamics as its therapeutic effects come into play.

Patient condition may interfere with expected effects of HBOT

Another important point to consider in the risk/benefit balance of HBOT for ICU patients is organ failure, which may interfere with the expected beneficial effects of HBOT. In particular, in case of respiratory failure, the intrapulmonary shunt will impair the expected rise in arterial oxygen pressure (P_aO_2) and, therefore, compromise HBOT efficacy. Similarly, in the case of circulatory failure, decreased cardiac output and arterial vasoconstriction will impair organ blood flow and tissue oxygen delivery. Thus, in an under-resuscitated critically ill patient, HBOT may be ineffectual because the expected rise in tissue PO_2 will not occur. Therefore tissue oxygenation monitoring such as transcutaneous oxygen pressure is mandatory in order to correctly evaluate the effects of HBOT.

Aside from this potential decrease in the beneficial effects of HBOT, ICU patients may be at a higher risk of adverse events in the chamber. In respiratory failure, pulmonary heterogeneity with air trapping increases the risk of barotrauma. Trauma and surgery may create new air-filled cavities with an increased risk of barotrauma (e.g., intracranial pneumatocele). O_2 toxicity may be enhanced because cerebral trauma, sepsis and pyrexia decrease the hyperoxic convulsion level, and pulmonary injury may increase the sensitivity of the lung to hyperoxic injury.

Hyperbaric environmental constraints on patient care

Hyperbaric centres have specific characteristics in terms of location, chambers, environment and safety. However, ICU patients also require specific conditions with respect to these three characteristics and they are often far removed from those of elective hyperbaric practice. These constraints are not necessarily insurmountable, but need to be analysed and mitigated before accepting an ICU patient for treatment.[5]

LOCATION

Hyperbaric chambers are vessels designed to support pressures exceeding atmospheric pressure. The patient has to be transported from the ICU to the chamber and back after each session. Transportation of a critically ill patient may expose them to an increased risk of deterioration and requires specially equipped trolleys or beds in order to continue patient monitoring and treatment during transfer; specially trained personnel and a specially formulated transfer management plan according to the Society of Critical Care Medicine guidelines.[6]

CHAMBER

Hyperbaric chambers are usually small compared to the recommended ICU room (26 m^2). This may pose several detrimental consequences:

- Nosocomial infection may be favoured because of three factors: inter-patient distance is reduced, increasing the risk for cross-contamination; hyperbaric chambers are often cluttered with multiple valves, pipes and devices, making disinfection difficult and inefficient;
- Available free space for the attendant and patient accessibility are reduced, so cross-contamination prevention measures and care procedures are difficult to apply consistently;
- Noise, inadequate control of temperature and humidity and confinement make the working environment unpleasant. High nitrogen partial pressure may induce nitrogen narcosis, which will impair personnel's ability to deliver proper care.

All these factors contribute to increased nurse/physician stress and may lead to increased errors in patient management.

PERSONNEL

ICU patients are under constant supervision by well-trained nurses and specialized medical staff. This level of medical/nursing education and training cannot be permanently guaranteed in some hyperbaric centres. However, this is a prerequisite before acceptance of an ICU patient for treatment. The most important rules concerning HBOT personnel caring for ICU patients are:

- The patient has to be under physician/nurse control in an ICU room;
- Usually, nurses attend the patient in the hyperbaric chamber, while physicians are available if intervention is necessary (personnel lock required);
- All personnel have to be medically fit and educated to work under pressure;
- All personnel have to be educated and trained to be able to care for intensive care patients.

PATIENT MONITORING

All of the monitoring devices used in ICU should be adapted for use in the hyperbaric environment.[7–9] These include:

Haemodynamics

- Electrocardiogram (ECG);
- Arterial pressure (non-invasive, invasive);
- Central venous pressure (CVP);
- PA catheter;
- Cardiac output (thermodilution, transthoracic bio-impedance, transoesophageal echocardiography);
- Mixed venous oxygen saturation (S_VO_2).

Ventilation
- Respiratory rate;
- Airway pressure;
- Tidal volume (V_T) (rotameter, pneumotachograph);
- Pulse oxymetry;
- Arterial blood gases;
  - Of little value when measurement is done outside the chamber;
  - Good value when measurement is done inside the chamber;
  - Easy when continuously measured by an intra-arterial probe;
  - Indirect evaluation by transcutaneous oxygen measurements;
- Expired gas measurements;
  - Measurement of end-tidal carbon dioxide partial pressure ($P_{ET}CO_2$) by standard mainstream methods is subject to errors; sidestream capnometry is reliable for measurement if performed outside the chamber at room pressure on a decompressed gas sample;
  - Measurements are best performed by mass spectrometer (requires special, expensive installation).

Neurological
- Intracranial pressure (ICP);
- Electroencephalography (EEG);
- Bi-spectral EEG analysis;
- Jugular venous oxygen saturation (S_JO_2);

Other
- Temperature;
- Urine output;
- Intra-abdominal pressure;
- Intra-compartmental pressure.

Tissue oxygenation

Evaluation is mandatory in ICU patients to check if the rise in PO_2 expected under HBOT is reached:
- Transcutaneous oxygen pressure (TCOM)
- Continuous arterial oxygen pressure (P_aO_2)
- Tissue oxygen partial pressure (P_tO_2
- For the future:
  - Tissue oxygen saturations (S_tO_2) and Cyto aa3 redox state by near-infrared spectroscopy (NIRS)
  - Lactate/pyruvate by microdialysis

TREATMENT DEVICES

The same rules apply to all therapeutic devices used in ICU:

Ventilation
- Mask and head hood may be easily used for non-invasive ventilation (NIV);
- Mechanical PEEP valve is preferred for continuous positive airway pressure (CPAP);
- Tracheal tube cuff must be water-filled; a foam cuff is a convenient alternative;
- Breathing gas must be correctly humidified;
- Tracheal aspiration must be accurately pressure-limited to avoid any mucosal injury.

Cardiac support
- Defibrillation is still a matter of debate due to safety reasons.[10] It is probably safe if the self-adhesive pads are placed and secured before the session and the defibrillator device is located outside the chamber. However, the clinical advantages of defibrillation inside the chamber under pressure, versus the traditional procedure (cardiac resuscitation, quick decompression and defibrillation at atmospheric pressure) are not established.
- External pacing (transthoracic and by intra-ventricular catheter) is safe if the device is placed outside, but should be validated after a risk analysis if the device is inside;
- Implantable pacemakers and defibrillators are safe up to 304 kPa;
- Artificial hearts are safe up to 405 kPa (at least on one patient!).

Infusion therapy
- Fluid administration by gravity: there is a risk of a decreased infusion rate and blood aspiration during compression, and uncontrolled infusion and gas embolism during decompression, related to the Boyle-Mariotte Law.
- Syringe pumps are safe if the soft key pad is open to ambient pressure (a cautionary note: some syringes have an air-filled space between the piston and the plastic tip).
- The infusion rate may be impaired during compression and decompression in infusion controllers, patient-controlled analgesic devices and insulin infusion pumps.
- Unplanned drug or device needs require an equipment lock to be permanently available.

Drainage and suctioning
- Intensive care patients often have multiple drainage systems. Most of these (e.g., pleural, mediastinal, pericardial and abdominal drains) require accurate, regulated negative-pressure drainage. High negative pressures may occur inadvertently during compression, with the consequent risk of organ injury and rupture. Conversely, low negative pressures or even over-pressurisation may occur during decompression, with risks of barotrauma, gas embolism and/or retrograde fluid flow.
- The aspiration pressure has to be set before the HBOT session and remain constant throughout.
- Manual adjustment is difficult and may expose the patient to inadvertent over- or under-pressurisation.
- To use the pressure difference between the chamber and ambient pressure, even with a vacuum regulator, may be dangerous.
- The best system involves creating a vacuum with a Venturi device and using a second stage regulator.

SAFETY ASPECTS

Any medical device introduced into a hyperbaric chamber may be associated with increased risk to patients and attendants, as the function of the device may be altered and compromise patient care and/or safety, integrity of the device may be altered (exposing occupants to the risks of

fire, explosion and gas toxicity) and improper use of the device may occur.

The high partial pressure and any increase in the fraction of oxygen in the chamber atmosphere combined with a combustible product and a source of ignition (e.g., electrostatic sparks or an overheated surface) constitute the classic "*Triangle of Fire*".

A major problem is the fact that manufacturers have to get prior approval to market any medical devices (in Europe: CE marking, in USA: FDA approval). All these approval processes require financial investments that may not be profitable as the market for medical devices to be used in a hyperbaric environment is small. As a consequence, many manufacturers do not apply for hyperbaric approval and thus, the responsibility for using such a device in a hyperbaric chamber is entirely that of the physician-in-charge.

Prior to installing a medical device in a hyperbaric chamber, the following rules must be followed:

- Make certain that it does not contain any closed compartments under atmospheric pressure and that the pressure in all compartments of the device is equivalent with that of the environment or that it is pressure-resistant to the working pressure of the chamber;
- Ensure, by conducting hyperbaric tests, that:
  - Controls, e.g., the keyboard pads, do not become distorted and function blocked;
  - Performance of the device probes do not deteriorate due to changes in pressure or this can be rectified;
  - Operation of the built-in electronics of the device is not compromised;
  - Display is not compromised;
  - Flow rates, pressures and frequencies with which the device dispenses any medical products are not compromised or, at least, are accurately evaluated;
  - In case of doubt, do not install the medical device in the chamber.

Conclusions

In the context of the ECHM-accepted indications for HBOT, ICU patients represent a specific group for which the risk/benefit analysis should be based both on the individual patient's condition and the hyperbaric centre capability.

ICU PATIENT MANAGEMENT

HBOT shall be included in the overall management of ICU patients so long as its benefit outweighs any perceived risks and does not delay or interrupt the overall management of the patient. Neither patient monitoring nor treatment should be altered or stopped during HBOT, but the physiological effects of HBOT must be all the more strictly evaluated because of the severe condition of the patient.

THE HYPERBARIC FACILITY

The hyperbaric chamber should be specifically designed for critically ill patients and fully equipped to allow continuation of patient monitoring and treatment. The hyperbaric chamber should be located in or around the immediate vicinity of the ICU and be run by a sufficiently large and well-trained team of physicians, nurses, chamber operators and technicians. All devices to be introduced into the chamber should be evaluated, tested and certified as safe in a hyperbaric environment and all procedures (standard and emergency) should be tested and written before being implemented.

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