

Hyperbaric intensive care technology and equipment

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Abstract

(Millar IL. Hyperbaric intensive care technology and equipment. *Diving and Hyperbaric Medicine*. 2015;45 March:50-56.) In an emergency, life support can be provided during recompression or hyperbaric oxygen therapy using very basic equipment, provided the equipment is hyperbaric-compatible and the clinicians have appropriate experience. For hyperbaric critical care to be provided safely on a routine basis, however, a great deal of preparation and specific equipment is needed, and relatively few facilities have optimal capabilities at present. The type, size and location of the chamber are very influential factors. Although monoplace chamber critical care is possible, it involves special adaptations and inherent limitations that make it inappropriate for all but specifically experienced teams. A large, purpose-designed chamber co-located with an intensive care unit is ideal. Keeping the critically ill patient on their normal bed significantly improves quality of care where this is possible. The latest hyperbaric ventilators have resolved many of the issues normally associated with hyperbaric ventilation, but at significant cost. Multi-parameter monitoring is relatively simple with advanced portable monitors, or preferably installed units that are of the same type as used elsewhere in the hospital. Whilst end-tidal CO₂ readings are changed by pressure and require interpretation, most other parameters display normally. All normal infusions can be continued, with several examples of syringe drivers and infusion pumps shown to function essentially normally at pressure. Techniques exist for continuous suction drainage and most other aspects of standard critical care. At present, the most complex life support technologies such as haemofiltration, cardiac assist devices and extra-corporeal membrane oxygenation remain incompatible with the hyperbaric environment.

Key words

Hyperbaric oxygen therapy, intensive care medicine, hyperbaric facilities, safety, equipment, patient monitoring, ventilators, review article

Introduction

Although relatively few intensive care units have the capability to provide hyperbaric oxygen treatment (HBOT) to their patients, it is clear that hyperbaric intensive care is feasible and that it can be delivered safely to appropriate

patients by experienced teams who have suitable technology. All critical care interventions should be subject to risk-benefit evaluations at multiple levels, including on a policy-making basis as to whether the intervention is used at all and when the technology and skills are available, whether to use the therapy in any particular patient at a particular time.

These principles apply equally to HBOT, and it is highly undesirable to embark upon HBOT for critically ill patients using 'makeshift' or 'minimalist' arrangements.

Whilst the potential benefits of HBOT should be independent of where and how HBOT is delivered, it is clear that the risk of treating critically ill patients depends heavily upon the type of hyperbaric chamber, its location, the experience of the clinical teams involved, and the equipment available. The critical care capability of some units is sufficiently good for HBOT to be used for sub-acute indications such as the promotion of wound healing or ischaemic tissue salvage in ventilated patients. More commonly, hyperbaric critical care will be reserved for situations where there is imminent threat of death from highly oxygen-responsive conditions such as gas gangrene. A recent review of hyperbaric critical care, as well as a series of four papers on medical equipment for multiplace chambers are particularly useful.¹⁻⁵ This paper builds upon these sources.

Monoplace chamber intensive care

Although monoplace chambers are generally regarded as unsuitable for critical care in Europe, there are some centres that have achieved high capabilities as a result of local expertise, ingenuity in creating custom adaptations and many years of clinical experience. The hyperbaric medicine facility at Salt Lake City, USA has developed what is probably the premier example of this, with capabilities to routinely ventilate, monitor invasive blood pressures, take blood gases and much more. This capacity has taken many years to develop and the expertise and equipment that make high-level monoplace critical care possible in Salt Lake City would be difficult to reproduce elsewhere. Conceptually, monoplace chamber critical care shares similarities with anaesthesia for neurosurgery or ENT surgical cases where the anaesthetist must remotely control all monitoring and the delivery of physiological and drug therapies. In some cases, monoplace chambers are taken to the intensive care unit (ICU) so as to avoid patient transport away from the critical care environment. Transfer from the ICU bed to a monoplace stretcher is still required, however, as is a change of ventilator and re-routing of fluid and monitoring connections through the chamber penetrators. This is all very time consuming and potentially disruptive of optimal critical care. The ventilators presently available for monoplace chambers are very basic units that have significant functional limitations. Most critically, the models of intravenous fluid pumps that were capable of pushing fluid into the chamber from outside have been discontinued, creating a potential crisis for all hospital patient care in locations that have only monoplace chambers. Further detail on the techniques used in monoplace critical care can be found in various papers and textbook chapters on the subject.¹

An alternative monoplace critical care configuration under development is the use of a large, air filled monoplace

chamber within which is located remotely controlled ventilation and infusion equipment, as well as the patient. This arrangement has the potential to allow more sophisticated ventilators to be used, along with a wider variety of infusion pumps, but any further development of this concept will be inherently tied to the availability of remotely controllable, hyperbaric-compatible ventilators and infusion equipment.

Multiplace chamber intensive care: the location of the chamber

The ideal hyperbaric chamber for critical care would be physically integrated into the ICU, or at least immediately adjacent, such that transport requirements are minimised. Ideally the clinicians looking after the patient in the ICU would continue to look after the patient in the hyperbaric chamber, or at least be close by, such that continuity of care direction can be ensured, with expert clinical back up immediately available should there be any problems.

More commonly, the hyperbaric chamber will be located at some distance, and there will need to be a 'philosophical' choice with respect to staffing. Hyperbaric oxygen sessions can be delivered using the staffing model usually used for transports to investigations like MRI or angiography where the intensive care team travels with the patient and provides continuity of care. Alternatively, the intensive care team can hand over care to a separate but appropriately qualified team. This care model mirrors transfers to the operating theatre team for surgery, with subsequent post-procedure transfer back to intensive care.

The chamber location and staffing arrangements will determine whether the hyperbaric unit can be supported by the existing critical care infrastructure such as blood gas analysers, resuscitation and 'difficult airway' equipment, etc., or whether dedicated support equipment will be necessary in the chamber vicinity.

The type of chamber

Hyperbaric intensive care is easiest if the floor space and features of the chamber closely resemble a normal intensive care cubicle. A number of the leading centres have achieved this through large rectangular chambers with doorways up to 1.4–1.5 m wide, and a critical care compartment floor area close to that of a small to medium-sized intensive care cubicle: 18–21 m². The optimal facility will also have lighting, temperature control, noise levels and internal equipment similar to an ICU, with hand wash basins in all relevant compartments. All of this is now demonstrably feasible, albeit at a cost, for new facilities. Existing facilities will not be able to change the basic size and shape of their chamber, but other features may possibly be retrofitted during an upgrade.

Medical gas services

Many items of critical care equipment require medical gas supplies in order to function. Hyperbaric chambers designed to facilitate high-level critical patient care should have medical gas outlets for oxygen and air that have the same connection types used in the rest of the hospital. These should be installed in a manner that ensures that the pressures and flows available meet the national hospital systems requirements both at the surface and under pressure, so that gas-utilising equipment such as ventilators can operate as normally as possible under pressure.

The performance of suction systems should also, ideally, match normobaric hospital standards, corrected for pressure. This has proven more technically difficult to achieve, however, and test methods have not been published or validated for medical suction at pressure. Whilst most systems are probably functionally adequate, it seems likely that variable and technically non-compliant flows and/or vacuum levels are unknowingly generated in many cases, especially during pressure changes.

A number of different approaches can be taken to provide in-chamber suction. The simplest approach is to use commercially available air-powered venturi suction units. Such systems can provide adequate suction of fluids but should not be used to scavenge ventilator gas exhausts as oxygen-enriched gas will be dumped into the chamber. Permanently installed suction systems generally use the differential pressure between the chamber interior and exterior to provide suction, which will only work when the chamber is at pressure unless the system is externally connected to the hospital suction system or a locally installed suction pump. In all such configurations, regulation is required to prevent excessive suction when the chamber is at pressure. It is also important to be aware that relatively small leaks of chamber air into the suction system can quickly overload the capacity of hospital suction pumps. Suction systems design needs to allow for system cleaning including disassembly if blockage occurs. Any filters need to be readily accessible for removal and cleaning or replacement when necessary. It is highly desirable for multiple suction outlets to be available for patients with multiple suction drains or intercostal catheters. At least some outlets should be fitted with a hyperbaric-tested vacuum regulator to provide continuation of low-level suction. Many commercially available low-suction regulators have been successfully used for this purpose without modification.

Electrical power

Although some chambers have standard alternating current power outlets as used in the country where the chamber is located (e.g., 220V, 50Hz or 110V, 60Hz), this is generally considered an excessive hazard. Most hyperbaric chamber safety codes and guidelines recommend only low voltage power installations or batteries, and a maximum power may

be cited. The relevant European standard, EN14931, includes some general recommendations on this subject and the NFPA 99 Healthcare Facilities Code used in the United States has some valuable detail that is very worthy of consideration in jurisdictions where this Code is not mandated.⁶

Unless a local design standard requires otherwise, it is recommended that electrical connectors be selected that cannot be confused or interconnected with other systems and that are screw-connected or otherwise protected against accidental disconnection under pressure. These should be supplied from dedicated medical-grade power supplies with battery or uninterruptable power supplies (UPS) back-up separate from other services such as lighting or entertainment. Attention needs to be paid to critically selecting which electrical systems are automatically disconnected in case of fire deluge operation. It may be necessary to supply multiple different voltages to meet the requirements of different items of critical care equipment.

Electrical safety rating

The patient care areas of an optimal hyperbaric critical care facility will be certified to the same electrical safety standards that apply to the hospital's ICUs. The chamber should also meet the same levels of electrical design, construction, protection systems and testing, although some of the special requirements for safe chamber installations may create barriers to certification according to normobaric hospital standards. It is arguable whether the highest level of 'cardiac protection' is needed as it is unlikely that invasive intracardiac pacing would be initiated or that electrocardiac mapping studies or open chest procedures would be undertaken in the chamber. The highest levels of electrical protection require completely conductive and grounded floor coverings and specially bonded earthing conductors for every metal item in the chamber, including all plumbing and metal panels. This is costly and may create maintenance difficulties. There are certain elements of electrical and electromagnetic radiation safety inherent in the metal construction of a chamber, provided there are only suitable low voltage electrical installations and suitable battery-powered devices. A critical design point for direct current (DC) power systems is that they should be ungrounded and therefore not capable of 'shorting' to the chamber steel.

There are high levels of electrical safety built into modern, proprietary intensive care monitors, whether they are operating off battery power, or installed outside the chamber with connections inside, and electrical supply coming from circuits fitted with low threshold residual current devices and circuit breakers that meet hospital electrical standards. In some cases, core balance transformers and/or line isolation monitoring may be used. Medical device standards generally require electrical equipment to 'fail safe' and not risk delivering a dangerous shock to the patient but the applicability of this in hyperbaric conditions should be assessed for each type of device. Continuity of electrical

grounding and circuit protection must be considered when designing battery back-up or UPS for medical devices in the chamber as many standard UPS installations can bypass or invalidate medical grade electrical protection systems.

Batteries

Many items of critical care equipment have rechargeable batteries that are primarily designed for patient transport and to ensure continuity of care during short duration power failures or accidental mains power disconnection. Provided the battery duration is sufficient and the battery type is tested and agreed to be safe for hyperbaric use, such battery-powered devices can be a good option for hyperbaric critical care. It should be noted that battery capacity tends to decrease with age and in some battery types, capacity decreases with frequent partial discharge as is a common usage pattern for much of the equipment routinely used in critical care. Unless the device has a long duration battery, regular 'run time' testing should be scheduled in addition to ensuring the best charging practices that are practical. A periodic battery replacement programme is highly desirable.

Batteries should not be charged under pressure as charging is the most common trigger for high-temperature battery failures. In addition, some battery types release hydrogen when charging – a very potent fire hazard. The chemistry of nickel metal hydride batteries is inherently safer in this regard. In some devices, charging when external power is connected cannot be disabled and, if so, robust systems will need to be put in place to prevent power connection in the chamber unless batteries are removed.

Lead acid batteries can be sealed or unsealed, with the electrolyte in liquid, gel or adsorbed form. Unsealed and liquid electrolyte type lead acid batteries risk acid spillage and are unsuitable as a result. Most authorities have great concerns about the hazard inherent in lithium chemistry batteries in the hyperbaric environment, given that pressure exposure may increase failure risk and many lithium battery types are capable of failing in a high-temperature 'melt down' mode. This can be a source of fire ignition that could in some cases continue even when immersed in fire-fighting water. With ageing, it is not uncommon for the lithium polymer batteries commonly used in mobile telephones, tablets and personal music players to swell before failing after a few years of heavy use. If any types of lithium batteries were to be assessed and approved as safe for hyperbaric use, it would be important to specify a number of usage cycles and an age at which to retire such batteries, well before the normally estimated end of useful battery life. It should be noted that repeated pressurisations anecdotally seem to reduce battery life at least in some cases.

Most electronic devices will also have one or more small long-life internal batteries to maintain timeclock and BIOS functions and memory of settings. Non-rechargeable lithium 'button cell' or circuit board-installed batteries are often

used for this function and these will require risk assessment when evaluating the safety of any individual device but most authorities consider the failure and fire risk of these small, sealed, single-use cells to be very much lower than larger and/or rechargeable batteries.

Beds and trolleys

Some smaller chambers will require patients to be transferred to a fixed chamber bunk for treatment, which involves undesirable patient handling but does have the benefit of minimising the risk of 'contraband' entering the chamber. For chambers that allow entry of a trolley, it is preferable for any patient transfers to the hyperbaric trolley to occur in the intensive care unit so as to minimise patient transfer risks and optimise care if instability results from physical handling. Ideally, the standard intensive care bed should be capable of being taken into the chamber. This has proven possible in recently constructed critical care chambers, subject to risk assessment of the bed components, and generally with the requirement to remove or disable high capacity battery powered bed-positioning systems. In these cases, the bed must have manual systems to enable emergency repositioning of the patient, for instance to the flat position for resuscitation or head down if required. Opinions vary with respect to the risk presented by grease in wheel bearings or actuators and hydraulic fluid, where relevant. The author's institution has exposed a range of standard critical care and general hospital beds to repetitive pressure cycles, and to saturation pressurisations followed by rapid decompression, in order to evaluate whether leakage of greases or fluids can be triggered. We have not experienced any such problems in 15 years. The bearings on most bed wheels are now either lubricant free or 'maintenance free', implying that any lubricants used are not volatile. Nevertheless, a good system of preventive maintenance and inspection prior to each hyperbaric session seems prudent.

Physiological monitoring

A primary component of critical care is continuous monitoring of a range of physiological variables, especially electrocardiogram, pulse oximetry, invasive or non-invasive blood pressures, end-tidal CO₂ and temperature. This is all possible, with varying degrees of sophistication and integration with the parent ICU systems. An optimal system will allow continuity of monitoring from the intensive care unit, during transport and throughout hyperbaric treatment with similar or identical equipment. All data should be viewable from across the intensive care network, with storage of monitoring and trend data as is available for all other patients; this subject has been detailed previously.⁷

Fluid infusion

In multiplace chambers, simple gravity-fed intravenous fluid infusions work as normal, provided attention is paid to the fluid level in the drip chamber and to venting of any non-

flexible containers. However, modern critical care practice requires multiple infusions to be controlled by infusion pumps and syringe drivers so that dose-critical agents such as inotropes can be delivered accurately and multiple infusions can be delivered without the need for continuous visual monitoring of multiple infusions to the detriment of attending to other matters. A range of infusion pumps and devices have been utilised in multiplace hyperbaric chambers with varying degrees of rigour of testing. Most are used in battery-powered mode but a few utilise a wired continuous power supply, including the CE-marked Fresenius Pilot(e) hyperbaric syringe driver. Unfortunately, manufacture of this infusion pump appears to have been discontinued recently.

There are significant clinical advantages if the same type of infusor can be used in the critical care unit, during transport, and in the hyperbaric chamber, as this removes the need for interruption of dose-critical infusions and reduces the risk of change-over errors. In addition to the list of devices published to date, the Alfred Hospital has rigorously evaluated the B-Braun Infusor Space syringe driver and the Carefusion Alaris System's Point of Care Unit and Pump Module. Both appear safe and have proved capable of working according to specifications when used on battery power in the hyperbaric chambers (publications pending) with some safety precautions noted for the Carefusion modular system and with a syringe preference for accurate performance of the B-Braun device at low flows. It is understood that several other infusors are presently in development or under evaluation at other centres, including some examples of infusors connected to remote controls which allow device control from outside the chamber.

There are also several brands of non-electrical fluid infusion systems available which use an elastomeric fluid bag inside a protective container to generate flow through a critical orifice. Some of these are known to be in use in monoplace and multiplace hyperbaric chambers and formal testing results for one such device are published in this issue.⁸

Passive drainage systems (wound, urinary, nasogastric)

Most passive drain tubes and bags can be accommodated provided attention is paid to the gas-containing patient anatomy as well as to the drain bag to ensure that excess pressure does not lead to expansion barotraumas of the patient or equipment, with the potential for dangerous or at least very unpleasant spillages during decompression.

Intercostal drainage

The dynamics of pleural drainage differ depending upon whether suction is important or not and, in particular, whether the patient has a pleural leak. Many hyperbaric units use simple 'Heimlich' one-way valves during HBOT with or without connection to an underwater seal drain and/or suction. A more sophisticated option is to utilise proprietary pleural drain units but some variations in function do occur

especially during pressurisation when a pressure differential arises between the increasing pressure of the ambient chamber air and the interior gas spaces of the device. Manual or automatic venting will be needed in most cases and it may be necessary to limit the rate of pressurisation.

Suction drainage systems

Proprietary suction drainage systems are commonly used as both sterile dressings and active therapy for surgical wounds (negative pressure wound therapy). Therefore, these can be in place on patients prescribed HBOT. These systems use proprietary electrical pumps that provide regulated and in some cases pulsed suction into closed containers. None of these pumps appear to have been validated as safe for hyperbaric use to date and many are mains power operated only. It is possible, however, to fabricate adapters to enable the connection of regulated low-pressure suction so that wound suction can be continued during hyperbaric exposure. This approach has been extensively used in the author's institution with a range of different suction containers being used inside the chamber. The efficacy and tolerability of in-chamber vacuum therapy, along with practical details of one simple but practical method of connection, have been published in this journal.⁹

Airway management

The need to manage the volume of the sealing cuff of endotracheal tubes is well known, with most units using water or saline replacement of the cuff air during HBOT. The compliance of a fluid-filled cuff is not as good as an air-filled cuff, however, increasing the risk of tracheal necrosis if fluid is left in situ. Therefore, most would recommend removal of the fluid and refilling with air after each hyperbaric session. Even with meticulous technique and adequate pharyngeal suction this does risk repeated small-volume aspiration into the lungs, which is undesirable, and as a result, automatic air-volume compensation systems are worth considering.

Ventilation

There are well-known challenges involved in selecting a ventilator for hyperbaric critical care. Unfortunately, some of the most successful hyperbaric ventilators are no longer manufactured or supported. The Oxford Penlon was an early pneumatically powered bellows ventilator with a design that enabled it to operate satisfactorily even with helium-oxygen gas mixtures in high-pressure saturation diving chambers at 20–30 bar. The Multivent version is also discontinued. The Siemens Servo 900C was one of the first and most successful of the modern-style, electronically controlled intensive care ventilators and it has proved capable of operating satisfactorily in clinical hyperbaric chambers in a range of installation configurations with the controls being operated either internally or externally depending upon the installation. Many of these remain in service but parts are becoming difficult to source.

A portable, hyperbaric-specific ventilator manufactured by Siare has been in service for some years, but this unit still has a number of limitations compared to what would be considered ideal. It is understood that a new, and much more sophisticated Siare model should be released in coming months and that this unit will offer multiple ventilation modes and an advanced graphic display/control interface.

An alternative, advanced, CE-marked hyperbaric critical care ventilator has recently been released, the Maquet Servo-i Hyperbaric. This unit is based upon Maquet's standard critical care Servo-I ventilator, and thus has the same dimensions, controls and displays as its 'parent' model which is widely used internationally. It is relatively large which may be a disadvantage for smaller hyperbaric chambers. The hyperbaric Servo-i has proved very serviceable and does not require any significant adjustments for pressurisation regardless of ventilation mode. In many ways, it meets the goals of optimal hyperbaric critical care in being a standard critical care device that is hyperbaric compatible. It is, however, presently marketed with only three ventilation modes available, which will limit the ability for this relatively expensive ventilator to be used in non-hyperbaric settings. It is understood that Maquet may offer upgraded capabilities for this ventilator via software update in the future, once the proposed additional modes and features are validated.

Many other, but not all ventilators are capable of being used in hyperbaric conditions. In general, the simpler anaesthesia and transport ventilators are more likely to function, albeit with some limitations and modifications of settings. Most 'full-feature' critical care ventilators will either not be electrically safe for hyperbaric use or will fail due to limitations of the pressure sensors or software systems intrinsic to the device.

Defibrillation

A stand-alone CE-marked portable hyperbaric defibrillator is now available (Corpuls). It is understood another should be available shortly (Haux). As an alternative arrangement a number of chambers have cables installed to allow an external defibrillator to be connected to internal adhesive pads, in some cases with safety interlocked switches to require two persons to activate a shock. However, the most common arrangement is to not have defibrillation available inside the chamber at all, on the basis that a 'shockable rhythm problem' is most unlikely during HBOT and the degree of oxygen dissolved in tissues provides for adequate time for a safe, urgent decompression for defibrillation at surface pressure in a 'doors-open' state. The issue of defibrillation is further explored in a recent publication.⁵

Blood gas analysis and biochemistry

Very few chambers have the capacity for blood-gas analysis and/or any biochemical testing at pressure. In most cases, arterial or venous blood samples will be transferred out for

external testing. This is generally satisfactory, although it is hoped that, in the future, some 'Point of Care' systems may prove hyperbaric compatible. Blood glucose will usually be ascertained as a by-product of blood gas testing but simple glucometers selected as hyperbaric-compatible have proved useful. It should be noted that not all glucometers designed for bedside and ambulatory use are hyperbaric compatible and the chemistry or electronics involved can deliver false results under pressure.

The medical device regulatory problem

A major issue for all who wish to provide critical care in the hyperbaric environment is the relevant national medical device regulatory system and its interpretation by the individual hospital. If local law or policies require all devices to be 'CE-marked' specifically for hyperbaric use, this will very much limit the choice of what is available for use. In other cases, the Medical Director of the hyperbaric unit may be able to choose to take responsibility for using medical devices 'off label' in an environmental sense – that is, to use a device that is approved for normobaric use for standard purposes but in a non-standard environment, the hyperbaric chamber. The formal legal situation will vary from country to country. This subject was addressed in some detail at the 2012 ECHM Consensus Conference in Belgrade, Serbia.^{10,11}

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Submitted: 11 November 2014; revised 05 January 2015

Accepted: 01 February 2015

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