Review article

Ultrasound in diving and hyperbaric medicine

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Abstract

(Gawthorpe IC. Ultrasound in diving and hyperbaric medicine. *Diving and Hyperb Med*. 2012;42(1):36-39.)
Ultrasound is a safe and effective imaging modality, the use of which is increasing exponentially in many areas of clinical medicine. In this article, we present what is, to our knowledge, the first in-chamber use of an ultrasound machine. We discuss the challenges this presented and how they were addressed, and explore the possible clinical applications that in-chamber ultrasound may deliver in hyperbaric medicine.

Key words
Ultrasound, hyperbaric medicine, equipment, review article

Introduction

Rapidly advancing technology has enabled ultrasound machines to become more affordable and compact, and to provide higher-quality imaging. Ultrasound provides a safe and effective, dynamic and repeatable form of imaging that can be performed at the patient bedside, and is free from the harmful effects of ionising radiation. The combination of these factors has led to ultrasound becoming increasingly popular across nearly every speciality of medicine.

Point-of-care ultrasound is defined as ultrasound performed and interpreted at the bedside and has led to the concept of the 'ultrasound stethoscope'.[1] Ultrasound education for non-imaging specialties is now relatively advanced, with guidelines established by many specialty colleges.[2] It is now being included in the syllabus for many speciality registrar training schemes and is being considered for inclusion in undergraduate training in many centres in the United States, the United Kingdom and Australia.[3] Some American medical schools are even beginning to provide their students with hand-held ultrasound machines for use during clinical rotations.[4]

A formal role for the use of point-of-care ultrasound in the field of hyperbaric medicine has yet to be clearly established; however, we see many possibilities for both clinical and research purposes. Within hyperbaric chambers, ultrasound transducers have been passed through access ports to study physiological parameters.[5–7] To our knowledge, ultrasound scanning with a machine inside the chamber has not been reported.

Potential applications of ultrasound in hyperbaric medicine

Ready and immediate access to an ultrasound machine within a recompression chamber could benefit patients in a number of ways.

PNEUMOTHORAX DETECTION

The role of ultrasound in the detection of pneumothoracies is well established in emergency medicine.[8] Divers with cerebral arterial gas embolism (CAGE) have pulmonary barotrauma by definition and may have an increased risk of developing a pneumothorax. If this occurs during hyperbaric treatment and remains undetected during ascent, the consequences are potentially catastrophic. Routine treatment of CAGE involves keeping the patient supine. For pneumothorax detection, a supine chest X-ray has a sensitivity ranging from 28% to 75%, whereas lung ultrasound has a sensitivity ranging from 86% to 98% even with minimal training.[9,10] The absence of the lung sliding sign, comet tail artefacts and the presence of a contact point confirms the diagnosis. The study can be successfully completed within 2–3 minutes.[11]

The clinical challenge of pneumothorax detection relies on identifying increased resonance to percussion and reduced breath sounds on the affected side. Early detection inside a noisy chamber can be very difficult and the decision to needle the chest without convincing evidence of pneumothorax is often difficult. The ability to image at depth with in-chamber ultrasound would allow detection of supine pneumothoracies before compression, and, if one developed at depth, would allow thoracocentesis to be performed when indicated. It would also allow clinicians to entertain other diagnoses when pneumothorax had been excluded as a cause for deterioration at depth.

CRITICAL CARE PATIENTS

Critical care patients inside the chamber pose unique problems to the hyperbaric physician. Some hyperbaric facilities run daily hyperbaric oxygen treatments for intensive care patients. In-chamber ultrasound provides a useful tool for a wide range of critical care applications. Pulmonary ultrasonography has been shown to be more

accurate than auscultation or chest radiography for the detection of pneumothorax, pleural effusion, consolidation and alveolar interstitial syndrome in the critical care setting.[12] Cardiac function can easily be assessed with bedside echocardiography (cardiac ultrasound), and its use has 'boomed' within intensive care.[13] The adequacy of intravascular filling can be accurately assessed by visualising inferior vena cava (IVC) diameter and determining respiratory variation.[14] Also, as a patient receives fluids, the changes in IVC parameters can be used to gauge response. Ultrasound has become the standard of care for procedural guidance and to confirm intravascular line placement.

DECOMPRESSION ILLNESS

The use of ultrasound is well documented in the measurement of intravascular bubbles.[15–18] Echocardiography has been confirmed as a viable alternative to the traditional aural Doppler for the assessment of decompression stress.[15–17] Equivalent bubble scoring scales between aural bubble assessment and visual echocardiographic assessment have been developed and continue to be revised.[18] Limited ultrasound is a simpler skill to learn and more easily reproducible than aural Doppler.[15,16] In-chamber use could provide us with further understanding of bubble formation and resolution during treatment.

RESEARCH

In-chamber ultrasound provides us with an excellent research tool to gain further information on diverse physiological parameters within the hyperbaric environment. With expertise on hand within the chamber, it alleviates the difficulties of second-hand image acquisition when transducers are passed through ports in the chamber.[6,7]

Selection and testing of an ultrasound device

Our requirements were for a portable ultrasound machine with good image quality that was suitable for chamber use at depth, with a range of ultrasound transducers suitable for echocardiography, abdominal imaging and vascular imaging. With the assistance of our Biomedical Services, Fremantle Hospital, we determined what were likely to be the major issues facing us in our quest to perform ultrasound under pressure. Key issues identified were:

- Electrical/power supply issues;
- Fire risk;
- Pressure/mechanical damage risk.

With our biomedical colleagues we approached various ultrasound distributors to discuss the possibility of testing their machines at depth.

ELECTRICAL/POWER SUPPLY ISSUES

There is little guidance on the testing and modification of electrical equipment for hyperbaric use. Review articles report on the use of medical devices under increased pressure, and basic safety principles and guidelines exist.[19–22] However, there are no Australian standards for equipment use in a high-pressure, oxygen-rich environment. The American National Fire Protection Association document NFPA 53 contains a recommended practice on materials, equipment and systems used in oxygen-enriched atmospheres and there are general recommendations from the European Committee for Standardisation.[23,24] In the absence of Australian standards, Fremantle Biomedical Services took these guidelines as a suitable standard for testing.

All the laptop-sized ultrasound machines on the market currently have a lithium-based battery system in tandem with a 240-volt mains supply. Lithium batteries have been shown to overheat under increased pressure and the increased risk of fire has deemed them unsuitable for chamber use at depth. Our in-chamber power supply is a filtered direct current (DC) power of 12 or 24 volts. Of the machines we tested only one, the Logiq e™, made by GE Healthcare, was able to function on a 24-volt DC supply; this markedly narrowed the field.

It was determined that for in-chamber use we would remove the internal batteries and connect to the 24-volt DC supply. In changing from the factory supplied alternating current (AC)/DC power converter to the straight 24-volt DC supply line, the grounding is lost. This was considered a hazard that may cause both electric shock and possible sparking and fire risk. A quick-blow ceramic fuse was therefore installed in the active line to prevent any such occurrence.

FIRE RISK

Fire and sparking risk is the most dangerous and likely hazard in a hyperbaric chamber. To minimise this risk, temperature of all components needs to be kept low, and equipment clean, dust free and well ventilated. The NFPA guidelines specify that the maximum surface temperature of any component within the chamber is to be limited to 85°C. Temperature recordings from the service diagnostic tools, which took around 100 samples during testing, demonstrated that the central processing unit heated up the fastest. The maximum temperature recorded was 64°C.

At 24 volts DC, the peak current being drawn was shown to be 2.13 amps without the probe and 2.5 amps with the probe. The NFPA guideline recommends that the maximum power of in-chamber devices is limited to 48 Watts. The peak power draw from the Logiq e™ is 60 Watts, 12 Watts greater than that recommended. After due consideration and with spark proof connectors in place, Biomedical Services were confident that, with the peak surface temperatures only reaching 64°C, the unit would run safely at pressure.

Dust can act as a flammable agent and it is important that potentially hazardous equipment within the chamber stay dust free. A maintenance plan was drawn up to ensure the ultrasound console was kept clean and free of dust.

PRESSURE/MECHANICAL DAMAGE RISK

The Logiq e™ contains no sealed regions susceptible to a pressure difference and the main chassis has two main airflow paths leading out to vents on either side of the device. The ultrasonic transducers are completely sealed, which could lead to problems with pressure difference although it was noted that transducers had previously been successfully used when passed through ports into chambers.[5–7]

THE PROCESS OF INTRODUCTION TO THE CHAMBER

Having addressed all the various concerns outside of the chamber, we proceeded to introduce the ultrasound machine to operation at increased pressure in sequential steps.

The ultrasound transducers: The ultrasound transducers, which contain piezoelectric crystals, were initially tested alone in the chamber. Image quality and integrity of the crystals were checked on the surface after the probes had been sent to increasing pressures up to 405 kPa.

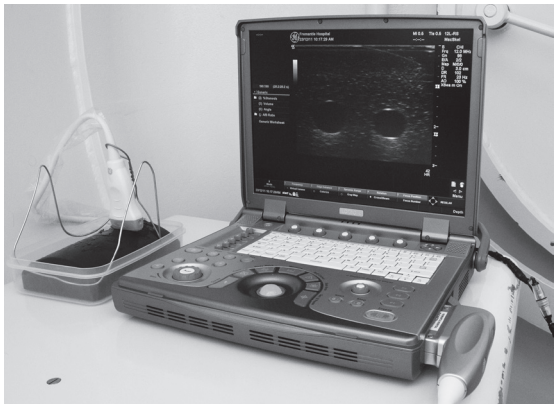
The ultrasound machine: After this assessment and the required modifications, the laptop ultrasound machine was certified safe to trial alone in the chamber. The internal batteries were removed, the unit connected to the 24-volt DC supply in the chamber, and the transducer held onto a phantom to provide a visible image through the chamber porthole (Figure 1). Temperature recordings were further checked during the unmanned trials within the chamber. The maximum temperatures did not exceed the 64^{O}C previously recorded. No new or unexpected issues were encountered.

Maintenance: The machine is to be tested monthly for preventative maintenance, primarily for removal of dust, a check of system logs, an electrical safety test and hard disk surface scan.

Introduction to clinical use: The Biomedical Services completed a modification report and a user's instruction guide. The first manned use of the entire ultrasound machine was carried out in April 2010. A group of consenting dual-qualified hyperbaric and emergency physicians went with the ultrasound machine to 405 kPa. One of the group was trained in ultrasound and carried out limited examinations as would be performed clinically within a hyperbaric chamber. Images were stored for review after the dive. The GE Logiq e™ ultrasound machine, after modification, provided images safely to depths up to 405 kPa, with no impairment of image quality.

Since testing, and with no alternatives available, the Logiq e™ ultrasound machine was purchased and modified for hyperbaric use. Biomedical Services certified it safe for manned use within the chamber and further testing on consenting volunteers was performed without problems.

Figure 1
The Logiq e™ ultrasound set up for the pressurised chamber trials



Ultrasound has now been introduced to clinical work and a number of the hyperbaric staff trained in its use. As well as those involved in our research projects, consent is now sought from all critical care patients to have the ultrasound in the chamber if required, and we have imaged over 30 patients without problems. All patients or their immediate family are required to give informed consent to have the ultrasound machine in the chamber. We have a safe working procedure and the machine use is carefully monitored by Biomedical Services as per the agreed protocol. We have received ethical approval for a number of research studies, including a formal echocardiography study at depth.

Discussion

As we have experienced in emergency medicine, the potential indications for ultrasound in hyperbaric medicine are expanding rapidly, particularly now we are able to perform ultrasound at depth. Having said this, it is important that users understand its limitations and the added safety aspects of in-chamber use.

In our unit, it has become standard-of-care to ultrasound the chest of all potential CAGE patients to exclude pneumothorax prior to treatment. Within the chamber under pressure, we have found ultrasound to be invaluable in assessing the fluid resuscitation status of septic patients. We have witnessed nitrogen bubble resolution inside the chamber with commercial divers undergoing surface decompression and now routinely monitor staff for bubble counts following patient treatments. We have picked up occult wound collections needing drainage in two patients undergoing treatment for non-healing wounds, facilitating successful healing.

The Fremantle Hyperbaric and Diving Medicine Unit, is currently in the process of finalising plans to move to a new site and construct a new chamber. At significant extra cost plain radiography facilities could be provided within the

chamber. Whilst this may occasionally be useful, with the successful advent of in-chamber ultrasound we feel this is unlikely to add significantly to the point-of-care imaging we can now perform.

If ultrasound is perceived as a useful addition to our field and a potential market exists, we may have an opportunity to work with the manufacturers to produce equipment that is compatible to our unique environment.

Conclusion

We believe ultrasound will have an important role to play in hyperbaric medicine and have shown that it can be used safely and successfully in the hyperbaric environment.

Acknowledgements

Thanks to Fremantle Hospital Biomedical Services, GE Healthcare for their support.

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Submitted: 10 April 2011
Accepted: 04 November 2011

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