Transthoracic Echocardiography (TTE) - A Tool to Monitor Unsafe Decompression Stress

Neal W. Pollock, Ph.D.
Center for Hyperbaric Medicine and Environmental Physiology
Department of Anesthesiology
Duke University Medical Center
Durham, NC 2710

Abstract

Decompression sickness (DCS) is associated with gas emboli (bubble) formation. While the lung is an effective bubble filter, several avenues exist for left ventricular gas emboli (LVGE) to arise. Since LVGE are believed to produce an elevated risk of neurological DCS, it is prudent to react conservatively if any are observed, regardless of symptom status. Two-dimensional transthoracic echocardiography (TTE) provides a technique to visualize circulating bubbles. TTE is being used to monitor the left heart during altitude decompression studies at a growing number of facilities. A training curriculum has been established at Duke University to credential technicians working with the devices.

Background

The etiology of neurological decompression sickness (DCS) is uncertain. Although it is associated with gas emboli (bubble) formation, the manner in which bubbles arise is not fully understood. Mechanisms may include autochthonous (*in situ*) formation in central nervous tissue or translocation of venous gas emboli (VGE) to the arterial path. Translocation may occur through intracardiac shunts, across the pulmonary capillary bed (transpulmonary passage), or via any of the variable venous-arterial anastomoses.

The lungs are normally very efficient at filtering gas bubbles from the blood. Intracardiac shunts, or short cuts, however, can allow some blood, and any bubbles present at that time, to bypass pulmonary filtration and be disseminated throughout the body. There are various types and degrees of intracardiac shunts. Atrial septal defects (ASD) and ventricular septal defects (VSD) provide direct communication between right and left atria and ventricles, respectively. The direction of flow depends on the pressure gradient between the respective heart chambers. The gradient is from left to right for the most part and blood flow through shunts therefore usually follows this path. There are, however, conditions in which shunting can be reversed. In the case of a large ASD, this can occur within a normal breathing cycle. Transient reversals may be promoted by immersion, strain-release techniques (e.g., Valsalva or anti-G maneuvers) and elevated pulmonary arterial or right atrial pressure. Large VSDs are usually identified in the fetus

or neonate and usually require surgical repair to prevent complications. Unobserved VSDs are more likely limited to physiologically insignificant left-to-right leaks.

One common form of ASD is a remnant of the fetal circulation – the patent foramen ovale (PFO). The valve-like communication between the atria is normally closed after birth as left atrial pressure rises. Tissue growth normally seals the flap within the first 24 months. However, ~25% of the adult population have some residual opening (Hagen et al., 1984; Lynch et al, 1984). While the degree of patency is negligible in the majority of individuals, 5-10% of the adult population may have PFOs that are functionally important (i.e., allowing a physiologically meaningful amount of shunting) (Fisher et al., 1995). Functional (or physiological) patency is thereby distinguished from anatomical patency. Problematically, the presence of a functional PFO appears to increase the risk of neurological DCS in divers (Wilmshurst et al., 1986; Moon et al., 1989; Wilmshurst et al., 1989; Bove, 1998; Schwerzmann et al., 2001).

While it is possible to screen individuals for PFO and exclude them from decompression exposure, this is not done by diving organizations for several reasons: 1) the risk of DCS, with or without PFO, is very small; 2) PFO is not the only means of developing arterial bubbles or DCS; 3) the risk associated with PFO can be reduced by employing decompression practices which minimize bubble formation; and 4) there is a small but measurable risk associated with the test used to identify PFO (i.e., bubbles are injected into the venous circulation to visualize any subsequent cardiac crossover) (James, 1990).

Implications for Decompression Research

Valid research requires a subject pool that is representative of the population at large. For decompression research, this precludes the exclusion of volunteers based on the presence of PFO despite the potential for elevated risk. The challenge is to be inclusive while protecting the long-term health of all participants.

The primary protection from laboratory-induced DCS is the ability to rapidly initiate treatment in response to symptom development. This facilitates quick resolution and minimal risk of complications or residual effects. The ability to evaluate significant decompression stress independent of symptoms offers another avenue for protection. While Doppler ultrasound has been used for some time to estimate global stress, more recent developments in echocardiography are allowing more directed monitoring of potentially high-risk conditions.

Ultrasound and Echocardiography

Doppler ultrasound was first observed to detect circulating gas bubbles more than 40 years ago (Franklin et al., 1961). Since that time it has become the principle tool for monitoring decompression stress outside of symptom development. The greatest

strengths of Doppler assessment are that it is non-invasive and can be quick to complete. The chief limitation is that the relationship between observed gas emboli and symptomatic DCS is not consistently strong. While the correlation can likely be improved by methodological changes, most decompression studies continue to rely on symptom development as the study end-point.

Echocardiography combines ultrasound imaging and Doppler flow detection technology. The procedures rely on transducers that transform energy from one form into another. Ultrasound transducers contain piezoelectric elements that emit sound waves (acoustic energy) when excited electrically. Sound waves transmitted through the body generate echoes when changes in density are encountered. Echoes return to the transducer-receiver and the acoustic energy is transformed back into electrical energy, processed, and displayed graphically. 'Gain' controls adjust the amplification of returning echoes to optimize the displayed image. Originally, transducers transmitted and received the same frequency. More recently, transducers have been developed to transmit at one frequency and receive at another frequency to reduce interference. The transmitted frequency is known as the fundamental or first harmonic frequency. The received frequency (second harmonic) is a whole number multiple of the fundamental frequency. For example, a device may employ 2 MHz fundamental (transmit) and 4 MHz second harmonic (receive) frequencies. This 'harmonic processing' improves image resolution and is generally employed as a standard when available.

Two-dimensional transthoracic echocardiographic (TTE) imaging can be used to visualize the heart in cross-sectional view. This allows simultaneous visualization of multiple heart chambers and major vessels. Doppler monitoring, on the other hand, is generally restricted to the evaluation of a single major vessel or heart chamber. While TTE can be used to quantify the gas emboli loads (Eftedal and Brubakk, 1997) in a manner similar to Doppler scoring (Spencer and Johanson, 1974; Kisman et al., 1978; Eatock and Nishi, 1986), its greatest strength may be in detecting gas emboli on the left side of the heart (i.e., left ventricular gas emboli or LVGE) that can be distributed systemically. Since LVGE are implicated as causative agents in neurological decompression sickness, this in an important capability. While the absolute risk of DCS is not known, the conservative approach during altitude decompression research trials is to treat the presence of LVGE, regardless of symptom status, as a test-termination criterion.

TTE Equipment and Use in Decompression Studies

Traditional two-dimensional clinical echocardiographic imaging systems are bulky in size and prohibitively expensive for most non-clinical applications (~$200-250K^{US}). The Brooks Air Force research facility was one of the few to employ these devices in altitude decompression studies. Fortunately, recent advances in miniaturization and technology have resulted in the availability of portable systems that provide adequate resolution for LVGE monitoring at approximately one-tenth the cost of the standard clinical systems.

The SonoSite SonoHeart Elite portable ultrasound device is currently being used at Duke University and will soon be used at collaborating labs (Defence Research Development Canada [DRDC, formally the Defence and Civil Institute of Environmental Medicine] and the Johnson Space Center). The unit weighs 5.7 lbs and has physical dimensions that are smaller than many laptop computers (13.3 in x 7.6 in x 2.5 in). Harmonics processing is available as an option (with 2 MHz transmit and 4 MHz receive frequencies).

The SonoHeart has been tested and certified for use in hypobaric conditions (at altitude equivalents up to 30,000 ft) in a development program conducted by NASA and Duke University. Testing is underway to certify the unit for use at shallow decompression stop depths. Standard precautions ensure the safety of the device in the closed hypo-/hyper-baric chamber environment. These include removal of the battery and location of the AC power supply outside the chamber (a DC power cable is brought into the chamber through a wall penetrator). In addition, a minimum 5 $L \cdot min^{-1}$ flow of nitrogen is directed into the underside of the device housing to eliminate oxygen from the warmest area and reduce the risk of combustion.

Pilot trials employing the injection of agitated saline and/or commercial ultrasound contrast agent (Optison®) have provided compelling evidence of the device's ability to visualize LVGE. The SonoHeart is currently being used for decompression safety monitoring as part of flying after diving and high altitude decompression studies. The device has been used in 122 subject-exposures in the flying after diving study between May, 2002 and February, 2003. One case of mild, pain only decompression sickness has been observed in these trials. The presence of VGE, monitored with Doppler ultrasound, was documented in two other subjects (Grade 1 VGE on the Spencer 0-4 grade scale [Spencer and Johanson, 1974]). No LVGE or neurological symptoms have been observed in the study to date.

Implications for Future Research

The use of TTE monitoring during decompression studies is likely to become a standard as a growing number of research laboratories adopt the procedures. It is anticipated that the presence of LVGE will continue to stand as a test-termination criterion for altitude exposure. The procedures for diving decompression are complicated by the fact that the stressor cannot be simply removed by returning the subject to ground pressure as it works for altitude decompression. The conservative approach for LVGE observed during or following diving decompression is prophylactic recompression. It will be important to learn more about LVGE frequency and the true risk relationship between LVGE and DCS to determine if prophylactic recompression is warranted.

Training Requirements for Local Credentialing

Our initial studies relied on credentialed cardiac sonographers to provide training and oversight of the monitoring program. Technicians inside the chamber established views and sent the signals outside for digital recording and projection. Sonographers located outside the chamber directed technicians and confirmed the presence or absence of gas emboli.

An in-house training program was developed once the monitoring protocols were established. The goal was to provide local credentialing of technicians trained to perform scans independent of sonographer oversight. The estimated training time is 34-40 hours depending on the background of the individual. The distribution of the training time is described in Table 1.

Table 1. Estimated Time Required to Train TTE Technicians

Training Component	**Duration (hours)**
Theory and Overview	
Orientation Lecture	1-2
Self-Study	1-6
Hands On Practice	
Small Group Training Sessions	10
Supervised Research Scans	15
Testing and Evaluation	
Written Competency Examination	2
Affirmation by credentialed cardiac sonographer	2
Continuing Education	
Round Table Recording Scan Reviews	3
Total	**34-40**

The orientation lecture covers ultrasound principles and equipment, cardiac anatomy, standard cardiac views and procedures, terminology and study protocols. Self-study relies on computer-based graphic reference material to improve visual orientation and identification skills. The time required for orientation and self-study varies with the experience of the trainee.

Hands-on practice involves both dedicated training sessions and research study experience. Trainees complete at least 10 separate, one-hour sessions of small group training. The maximum student to instructor ratio is 3:1 (either clinical sonographers or locally credentialed TTE technicians serve as instructors). Instructors direct student technicians verbally to improve imaging techniques and mastery of standard reference terminology. Students scan a minimum of three different subjects (employing all three standard views) per session.

Student technicians deemed competent by small group instructors serve as intern technicians during research studies. A credentialed cardiac sonographer supervises intern activity. The supervisor may be physically located with the intern or present via radio/video links when scans are conducted in working pressure chambers. Interns serve as supervised research study technicians for a minimum of three complete research studies, monitoring a minimum of 12 different subjects with a minimum of three scans (one baseline and two trial scans).

The written examination covers cardiac anatomy, basic principles of ultrasonic monitoring, operating characteristics of the available devices, basic scanning techniques, and protocols to be followed during research studies. The criterion-based examination has a minimum passing score of 80%. Individuals failing to achieve passing grades are allowed to complete a revised examination in no less than 30 days.

Local credentialing is issued when the training requirements are met and the supervising sonographer affirms that the candidate can reliably establish appropriate views with acceptable speed and proficiency. Candidates must obtain a stable and clearly interpretable image via one of the three standardized views on a new subject within three minutes and follow this with a 90% continuously-interpretable 60 second recording including rest (30 seconds) and movement (30 seconds following three repetitive, maximal one-second isometric single limb contractions) phases.

Both credentialed and trainee technicians participate in continuing education activity to improve and/or reinforce competency and promote standardization of techniques. Recorded research scans from previous studies and/or training sessions are presented for group review and discussion. Credentialed technicians must participate in round table review sessions at least quarterly or as issues arise.

Conclusions

The availability of relatively inexpensive, two-dimensional transthoracic echocardiographic devices which enable visual monitoring of the left heart can improve the safety of decompression studies by identifying LVGE before they are distributed systemically. Although we do not know the absolute risk, it is prudent to suspend altitude exposure if LVGE are observed, regardless of symptom status. Monitoring protocols and a training program have been established for decompression studies conducted at Duke University. Further research is required to determine the true risk relationship between LVGE and DCS.

Literature Cited

Bove AA. Risk of decompression sickness with patent foramen ovale. Undersea Hyperbar Med 1998; 25(3): 175-178.

Eatock BC, Nishi RY. Procedures for Doppler ultrasonic monitoring of divers for intravascular bubbles. Department of National Defence: Defence and Civil Institute of Environmental Medicine (DCIEM) Report No. 86-C-25, 1986, 28 pp.

Eftedal O, Brubakk AO. Agreement between training and untrained observers in grading intravascular bubble signals in ultrasonic images. Undersea Hyperbar Med 1997; 24(4): 293-299.

Fisher DC, Fisher EA, Budd JH, Rosen SE, Goldman ME. The incidence of patent foramen ovale in 1,000 consecutive patients. A contrast transesophageal echocardiography study. Chest 1995; 107(6): 1504-1509.

Franklin DL, Schlegel W, Rushmer RF. Blood flow measured by Doppler frequency shift of back-scattered ultrasound. Sci 1961; 134(3478): 564-565.

Hagen PT, Scholz DG, Edwards WD. Incidence and size of patent foramen ovale during the first 10 decades of life: an autopsy study of 965 normal hearts. Mayo Clin Proc 1984; 59(1): 17-20.

James PB. Safety of contrast echocardiography in screening divers (letter). Lancet 1990; 336(8727): 1389-1390.

Kisman KE, Masurel G, Guillerm R. Bubble evaluation code for Doppler ultrasonic decompression data. Undersea Biomed Res 1978; 5(suppl 1): 28.

Lynch JJ, Schuchard GH, Gross CM, Wann LS. Prevalence of right-to-left atrial shunting in a healthy population: detection by Valsalva maneuver contrast echocardiography. Am J Cardiol 1984; 53(10): 1478-1480.

Moon RE, Camporesi EM, Kisslo JA. Patent foramen ovale and decompression sickness in divers. Lancet 1989; II(8637): 513-514.

Spencer MP, Johanson DC. Investigation of new principles for human decompression schedules using the Doppler blood bubble detector. Office of Naval Research Tech Rep ONR Contract N00014-73-C-0094, 1974.

Schwerzmann M, Seller C, Lipp E, Guzman R, Lovbald KO, Kraus M, Kucher N. Relation between directly detected patent foramen ovale and ischemic brain lesions in sport divers. Annals Internal Med 2001; 134(1): 21-24.

Wilmshurst PT, Byrne JC, Webb-Peploe MM. Relation between interatrial shunts and decompression sickness in divers. Lancet 1989; II(8675): 1302-1306.

Wilmshurst PT, Ellis BG, Jenkins BS. Paradoxical gas embolism in a scuba diver with an atrial septal defect. Brit Med J 1986; 293(6557): 1277.