Ultrasonic detection of decompression-induced bubbles

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Detection of gas emboli (bubbles) using ultrasound is a principle tool for monitoring decompression stress short of symptom development. Decompression-induced bubbles were first observed 47 years ago at the Virginia Mason Research Center as audible signals from sheep being monitored with a Doppler ultrasonic flowmeter.[1] Bubbles were later observed in human divers following decompression.[2] Aural detection of decompression-induced bubbles usually employs continuous-wave Doppler ultrasonic bubble detection (DUBD) using transcutaneous transducers to monitor a three-dimensional volume of blood in the precordial region (pulmonary artery or right ventricle of the heart) or peripheral veins such as the subclavian. Pulsed DUBD may provide more sensitivity and reduce background noise since 'range-gating' can be used to look at a specific distance from the transducer where bubbles are expected. However, it is more difficult to use, particularly with multiple subjects who are measured serially, and not widely applied in decompression studies. In either case, the portability of the instruments makes them useful for both laboratory and field studies.

The use of two-dimensional (2D) echocardiography to look for bubbles in the chambers of the heart is a more recent development.[3] 2D systems can provide a cross-sectional view along a single plane of all four chambers of the heart. Thus, unlike DUBD systems that assess only blood prior to pulmonary filtration, 2D imaging systems can also assess blood that will be sent systemically. Initially, 2D scanning devices were of sufficient bulk to be limited to laboratory studies. However, within the last 15 years, battery-operated portable units with sufficient resolution have become available for field studies. Technological advances, particularly harmonic processing, which allows analysis of less noisy signals at a harmonic frequency than at the return of the fundamental frequency sent out by the device, have made it possible to achieve image resolution close to that of standard clinical laboratory instruments. While transoesophageal echocardiography offers better resolution, transthoracic echocardiography is more appropriate for the relatively prolonged and repeated sampling used in decompression studies and is generally adequate to identify highly reflective gas bubbles.

DUBD requires observers who have the aural skills (and aptitude) to identify and semi-quantify bubbles in the complex signals arising from blood flow and heart motion artifacts. Bubbles are usually graded with one of two common scales. Disparities in technician skill, technician bias, signal quality and the grading scales used create a degree of inherent subjectivity in grading. Automated detection and counting systems, whether hardware-based or software-driven, have long been desired but difficult to produce in a robust form. 2D echocardiography, on the other hand, can produce visual representations of bubbles, potentially more easily assessed with automated counting algorithms. It remains to be seen how such systems can address the confounding introduced by bubbles in the blood volume either not passing through or repeatedly passing through the imaging plane.

Other major challenges are the estimation of bubble size and total gas volume when direct measurement is not available for confirmation. While dual frequency ultrasound holds potential for future bubble sizing (the first pulse excites bubbles of a diameter related to the ultrasound frequency and the second pulse identifies vibrating bubbles; a sweep of frequencies could identify a range of bubble sizes), the issues are complex. The shape of bubbles, for example, particularly larger bubbles, can be substantially distorted, potentially affecting size estimates. While current efforts can be valuable, any size and volume estimates must be considered very critically and with substantial restraint.

A final practical challenge is the comparability of different methods of grading bubbles. While there has been some evaluation of sequential DUBD and 2D scans, such efforts have been completed with very few of the many devices available. Questions of comparability are likely to increase as technology evolves and resolution continues to improve. The evolution of 2D imaging has become apparent in recent reports documenting a greater than expected frequency of bubbles in the left heart. Classically, left heart bubbles have been associated with an elevated risk of serious decompression sickness (DCS) since they have bypassed pulmonary filtration and are about to be sent forth systemically; the jump in observations with current devices (in asymptomatic subjects) suggests that their impact in decompression stress likely requires a more nuanced assessment.

While the relationship between bubbles and DCS is not simple, there is a clear association. Practically, bubbles occur far more frequently than DCS, sometimes following exposures that have very good safety records. The great utility of bubble assessment is likely to remain, not in determining absolute decompression risk, but in assessing relative decompression stress, in studies with a repeated-measures design. Bubble studies can be useful in developing and validating dive tables and/or in evaluating and modifying dive profiles and procedures. Repeated-measures design is very important given the marked inter-individual variability in bubble expression. Intra-individual variability will remain a concern, moderated by the tightest controls feasible.

In this issue, two papers consider 2D ultrasound systems to detect and quantify decompression stress. Blogg et al provide a review of the comparability of Doppler and 2D imaging technologies and evaluate the impact of harmonic processing and estimates of bubble load by obtaining paired 2D ultrasound images made using conventional and harmonic imaging.[4] Germonpré et al look at 2D imaging procedures, bubble grading, statistical methodologies for determining inter- and intra-rater agreement, and how a frame-based bubble counting system can improve agreement. The frame-based system allows bubbles to be treated as a continuous variable and may, perhaps, ultimately lead to computer-based algorithms for real-time analysis.[5]

A third paper in this issue, by Doolette et al, analyzes sample sizes required for sufficient statistical power to assess the differences in DCS risk between two decompression schedules when using observations of bubbles (that may have substantial variability) as an endpoint.[6] Paired samples (from subjects monitored with 2D echocardiography) of different sizes were investigated. The considerations raised in this paper may provide guidance in estimating appropriate sample sizes for future studies using observed bubbles for comparison of different dive profiles. While these authors employed a somewhat novel scale, it is possible that the methods described can be applied as a general standard to a variety of scales.

The common thread in these three papers is 2D imaging. They reflect a trend in decompression research towards a greater reliance on these techniques. Key benefits are their increased sensitivity and the ability to assess both sides of the heart. Still, despite these benefits, the relatively high cost of 2D systems and the extensive record of DUBD studies will undoubtedly keep DUBD technology in play, demanding ongoing attention to comparability.

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