Review article

Ultrasound detection of vascular decompression bubbles: the influence of new technology and considerations on bubble load

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Abstract

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Introduction: Diving often causes the formation of ‘silent’ bubbles upon decompression. If the bubble load is high, then the risk of decompression sickness (DCS) and the number of bubbles that could cross to the arterial circulation via a pulmonary shunt or patent foramen ovale increase. Bubbles can be monitored aurally, with Doppler ultrasound, or visually, with two-dimensional (2D) ultrasound imaging. Doppler grades and imaging grades can be compared with good agreement. Early 2D imaging units did not provide such comprehensive observations as Doppler, but advances in technology have allowed development of improved, portable, relatively inexpensive units. Most now employ harmonic technology; it was suggested that this could allow previously undetectable bubbles to be observed.

Methods: This paper provides a review of current methods of bubble measurement and how new technology may be changing our perceptions of the potential relationship of these measurements to decompression illness. Secondly, 69 paired ultrasound images were made using conventional 2D ultrasound imaging and harmonic imaging. Images were graded on the Eftedal-Brubakk (EB) scale and the percentage agreement of the images calculated. The distribution of mismatched grades was analysed.

Results: Fifty-four of the 69 paired images had matching grades. There was no significant difference in the distribution of high or low EB grades for the mismatched pairs.

Conclusions: Given the good level of agreement between pairs observed, it seems unlikely that harmonic technology is responsible for any perceived increase in observed bubble loads, but it is probable that our increasing use of 2D ultrasound to assess dive profiles is changing our perception of ‘normal’ venous and arterial bubble loads. Methods to accurately investigate the load and size of bubbles developed will be helpful in the future in determining DCS risk.

Key words

Doppler, bubbles, venous gas embolism, arterial gas embolism, decompression sickness, diving research, review article

Introduction

ULTRASOUND MEASUREMENT OF VASCULAR BUBBLES: RECENT OBSERVATIONS

It is well accepted that divers commonly develop venous gas emboli (VGE) on decompression. Most will never be aware of their presence, as the bubbles are often ‘silent’, without accompanying symptoms of decompression sickness (DCS). Bubbles form from supersaturated gases in the tissues or blood upon decompression and can occur after surprisingly shallow hyperbaric exposures.[1] For example, in one study, it was concluded that 50% of humans would be expected to develop VGE upon decompression after saturation at only 135 kPa (3.5 metres’ sea water, msw).[2]

The significance of VGE is their relationship to the risk of DCS. Studies have shown that the absence of VGE correlates well with the absence of DCS; in other words, if bubbles cannot be detected, then it is unlikely that symptoms of DCS will occur.[3–5] It also appears that the number of bubbles is proportional to decompression stress and the higher the venous bubble load, the more likely DCS is to occur, although the relationship is not direct.[6] Large numbers of VGE imply a very high free gas load, increasing the risk of clinical symptoms.[6]

In order to assess the number or load of bubbles in the body, two methods have been used: aural Doppler ultrasound monitoring and visual two-dimensional (2D) ultrasound imaging. Both methods most often focus on the cardiac region, observing venous bubbles as they return from the body to the right heart and into the pulmonary artery, though an important benefit of 2D imaging is that it also provides a simultaneous view of the left heart and any bubbles present there. Doppler methods remain essentially the same as when they were first developed in the 1960s. However, 2D ultrasound imaging has progressed; while conventional ultrasound processes only one returning signal, the more recently introduced harmonic imaging increases resolution and contrast of the images and allows differentiation between smaller objects.

In 2011, a study was presented comparing the link between VGE load and DCS risk.[7] Sixty-nine no-decompression dives were performed by 12 divers, all ranging in depth between 18 and 33 msw. Harmonic ultrasound imaging was used to assess bubble loads in the divers after they exited the water. The dives produced a considerable number of VGE in all divers, with most dives resulting in an Eftedal-Brubaak grade 4 (55 of 69 dives).[8,9] Five of the 12 divers also had arterial bubbles following 11 of 69 dives.[7]

We were surprised that so many VGE had been observed and, at the 2010 meeting of the European Undersea and Baromedical Society, we speculated that this was owing to the harmonic ultrasound technology and the greater resolution it afforded. Did this new technique allow smaller bubbles, previously invisible to conventional ultrasound, to be seen? It was also noted that left-heart bubbles were found in a greater percentage of the subjects than might have been expected. It is highly unlikely that more bubbles (arterial or venous) are being produced by today's divers; a simpler explanation is that we now have the ability to discover them via ever-improving technology.

This study examines the present techniques and equipment that are commonly used in decompression ultrasound, via a review of the literature. In order to test the hypothesis that harmonic imaging might reveal bubbles that were previously 'invisible' using conventional imaging, it also includes a simple study comparing images made with 'harmonics switched off' (conventional mode) and 'harmonics on' and goes on to discuss the relevance of bubble size and load to the risk of DCS.

Current methods of bubble measurement

DOPPLER ULTRASOUND

Doppler ultrasound was the original method, first reported by Spencer and Campbell in 1968, to detect VGE in the body associated with decompression.[9] Despite some improvements in methodology and transducer technology, the technique and equipment have remained relatively similar to the present day, whereby a well-trained operator applies an ultrasound transducer to the body that transmits a signal at a particular frequency. The operator then listens to the difference in frequency between the transmitted and received signal (that has been Doppler-shifted in frequency by moving objects such as red blood cells and bubbles in the blood). Gas bubbles are more efficient scatterers of ultrasound waves than red blood cells and are thus easily discernable.

The Doppler technique has been used by many workers across the years to detect bubbles and the information collected from both animal and human subjects forms a large data bank that may be used to compare the severity of decompression profiles, giving the method continuing relevance today. Smaller, more portable Doppler units with longer battery life also make the technique attractive for use on dive boats and the like. Limitations include the difficulty and time investment involved in training operators correctly, that information can be obtained only from one site at a time (for example the presence of arterial bubbles cannot be investigated whilst monitoring venous sites) and not being able to quantitatively assess the size of the bubbles.

Doppler measurements are usually evaluated using the Kisman-Masurel (KM) bubble evaluation code, or the Spencer code.[6,10] These methods are relatively subjective, and rely heavily on the operator having a good ear for the signal and being well trained and practised in using the grading scale. The KM code is generally preferred for its greater flexibility and sensitivity in grading scores, as it takes into account three components of the bubble signal. The first component assesses the number of bubbles produced per cardiac cycle (frequency), graded on a scale of 1 to 4 and is noted over at least 10 heart beats. The second component assesses the proportion of cardiac heart beats containing the bubbles (percentage), and the third considers the 'loudness' (amplitude), of the bubble signal using the background blood flow sounds as a reference. Once the three-part code has been determined, it is transformed into a KM grade, from 0 to IV, which aims to give a sense of physiological severity to the data. It should be noted that the scale is highly non-linear in nature, both in regard to the number of bubbles and to the corresponding risk of DCS; the resulting data should be handled with that in mind. Measurements are also often taken after movement, for example, a deep knee bend which, if bubbles are present, will produce a surge back to the heart that is easy for the operator to identify and helps to remove any ambiguity. Resting and movement measurements are always made separately and denoted when reporting results.

2D VISUAL ULTRASOUND IMAGING (ECHOSONOGRAPHY)

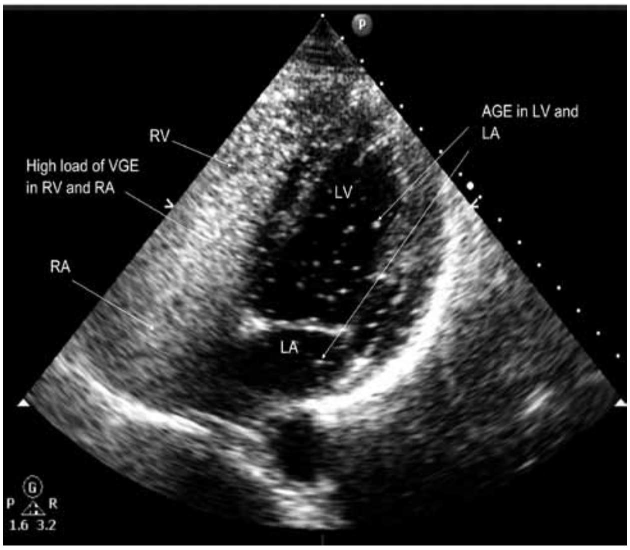
The second method of evaluating decompression bubbles is via the use of visual 2D ultrasound (echosonography) imaging systems. This is a comparatively young art in the field of decompression physiology, but it offers a number of benefits over Doppler, including an immediate impression of the bubble load in both the left and right heart (Figure 1), and ease of monitoring. It has been demonstrated that relatively little training is needed to accurately perform grading of 2D images although it is harder to reliably capture high-quality scans.[8] In contrast, learning to grade Doppler data may take a considerable time (months) to perfect. The 2D ultrasound technique has been used to assess human decompression bubbles in the heart since the late twentieth century and is growing in popularity, particularly as the once prohibitive price and size of imaging units is decreasing and, importantly, their image quality is improving.

Initially, the quality of the 'conventional ultrasound' images was such that 2D ultrasound was not as effective in assessing bubble loads as the use of Doppler ultrasound operated by experienced personnel. As for 2D visual data, a grading

Table 1
Relationship between Kisman-Masurel (KM) grades, Eftedal-Brubakk (EB) grades and bubble counts[3]

KM grade	0	I-	I	I+	II-	II	II+	III-	III	III+	IV-	IV
EB grade	0	1	1	1	2	2	2	3	3	4	4	5
Bubble count (bubbles cm^{-2})	0	0.01	0.05	0.1	0.15	0.2	0.3	0.5	1	2	5	10

Figure 1
2D ultrasound image showing bubbles in both sides of the heart of a degree (EB Grade 4C / 5) such that the outlines of the right ventricle (RV) and atrium (RA) cannot be discerned; bubbles (VGE and AGE) can be seen in both the left ventricle (LV) and atrium (LA)



system is necessary to evaluate the images and the most commonly used, the EB grade, was developed by Eftedal and Brubakk in 1997:[8]

0 – No bubbles;
1 – Occasional bubbles;
2 – At least one bubble every four cardiac cycles;
3 – At least one bubble every cardiac cycle;
4 – At least one bubble per cm^2 in every image;
5 – White out, single bubbles cannot be discriminated.

This simple system also relies on a degree of subjectivity. The agreement of the KM Doppler and the EB visual grading scales has been assessed for comparative purposes and was found to be good generally, though direct conversion from one scale to another should probably be avoided.[11] A bubble-counting system has also been developed, based on the number of visible bubbles in the observed field, providing a quantifiable measure of bubbles per square cm.[12] The relationship between these three techniques is shown in Table 1.[12]

The next stage in the development of the technology, harmonic ultrasound, was commonly introduced in the late 1990s.[13] It has recently been introduced to decompression physiology, although investigations into its use for bubble detection began as far back as the 1970s. Originally developed for use with ultrasound contrast microbubbles for clinical purposes, it was observed that the images acquired prior to the arrival of the contrast medium were of better quality than the fundamental signal (as processed by conventional instruments). Because of harmonic technology, many improvements to the quality of images have been made in recent years, including visualisation of smaller objects and improved contrast resolution, meaning that layers of grayscale in the image can be visually differentiated more easily. In simple terms, smaller bubbles should become more apparent and the image should be clearer.[14] The majority of modern ultrasound imaging systems now employ this harmonic principle. That this technology can be contained in small, portable, less expensive, dive-research-friendly units may go some way to explain why more bubbles, both venous and arterial, are being observed.

DOPPLER VERSUS IMAGING.

Comparing the relationship between the aural and visual grading methods with the bubble-count method (Table 1), it becomes obvious how highly non-linear the KM and EB grading systems are, particularly at the higher end of the grading scales.[3] For example, a single move from I+ to II- on the KM scale, or 1 to 2 on the EB scale, equates to a jump from 0.1 to 0.15 bubbles cm^{-2} in terms of bubble count. Moving from a KM III+ grade to IV-, both equating to a grade 4 on the EB scale, is comparable to a much larger move from 2 to 5 bubbles cm^{-2}.

In a recent investigation, KM Doppler grades using a Doppler Bubble Monitor, DBM9008 (Techno Scientific, Ontario, Canada) and harmonic 2D images (from a Philips CX50, Philips Healthcare, Stockholm, Sweden) of precordial VGE graded on the EB scale were compared directly (unpublished observations). The study was carried out to determine whether the harmonic technology would now render Doppler and 2D ultrasound non-comparable, whereas previously, conventional ultrasound imaging and Doppler were found to be comparable.[11] It was suggested that any smaller bubbles detectable to harmonics might be the reason for the perceived increase in observed venous and arterial bubbles, as described by others.[15] If this hypothesis were correct, then the EB grades should be lifted up a level or two against the KM grades. However, this was not the case. The harmonic imaging and Doppler data collected over 2 h post-decompression, from subjects who had been placed in a dry hyperbaric chamber compressed to 283 kPa for 100 min (RN Table 11[16]) were still generally found to be in agreement and in accordance with Table 1, both in the discovery and grading of bubbles. Hence, the findings also suggested that the majority of bubbles produced following decompressions in the study fell within the size range (circa 30 μm in diameter and above) of Doppler detection (these observations were reported as an abstract at the 2010 Undersea and Hyperbaric Medical Society meeting).

Conventional ultrasound versus harmonic ultrasound – an experimental study

INTRODUCTION

In light of the above unpublished observations, a study was carried out to compare paired harmonic and conventional images on the EB scale. In this way, the possibility that harmonic ultrasound could reveal bubbles previously invisible to conventional imaging post hyperbaric exposure was investigated.

METHODS

The study used ultrasound images that were recorded following a number of different dives made in the autumn of 2012. Subjects included male divers from the Swedish and Danish Navy and the study complied with the Declaration of Helsinki (2008). Images were recorded after open-water trimix dives with closed-circuit rebreathers and after trimix dives with semi-closed rebreathers in a hyperbaric chamber attached to a wet-pot. Dive profiles varied considerably, ranging from a dry introductory chamber dive, a wet dive to 30 m for 25 min, and deep-water dives made to 90 m with a bottom time of 20 min. The profiles are not included here, as it is the comparison of the paired grades that is of interest to this study, rather than the bubble loads provoked by the varying dive profiles.

On surfacing, 2D ultrasound measurements were made from five minutes to two hours post surfacing. When bubbles were present and the images were of reasonable quality, two recordings were made in a randomised order, one with harmonics switched on and another with harmonics switched off. The unit used, a Philips CX50 (Philips Healthcare, Best NL), allows the switch from harmonic to conventional ultrasound to be made easily, using a toggle switch. An attempt to include at least one set of recordings from each subject was made and the time taken between paired measurements was kept to a minimum. Each image was recorded after the subject was asked to make a move from the left lateral decubitus position, roll onto their back and then return to their starting posture, in order to try to standardise the bubble load returning to the heart on each of the measurements.

In total, 69 paired images were included in the study, taken from different subjects. The recordings were then played back for grading on the EB scale by a single, experienced operator. It was impossible to carry out blind grading of the data, as it is obvious as to which mode, conventional or harmonic, is being played back. The quality of the image (in terms of contrast and grayscale) is far superior in the harmonic mode and is instantly recognisable.

STATISTICAL ANALYSIS

Fisher's exact test was used to compare whether mismatched pairs of EB grade were more common with high (EB 3) or low (EB < 3) bubble loads (*P* < 0.05).

RESULTS

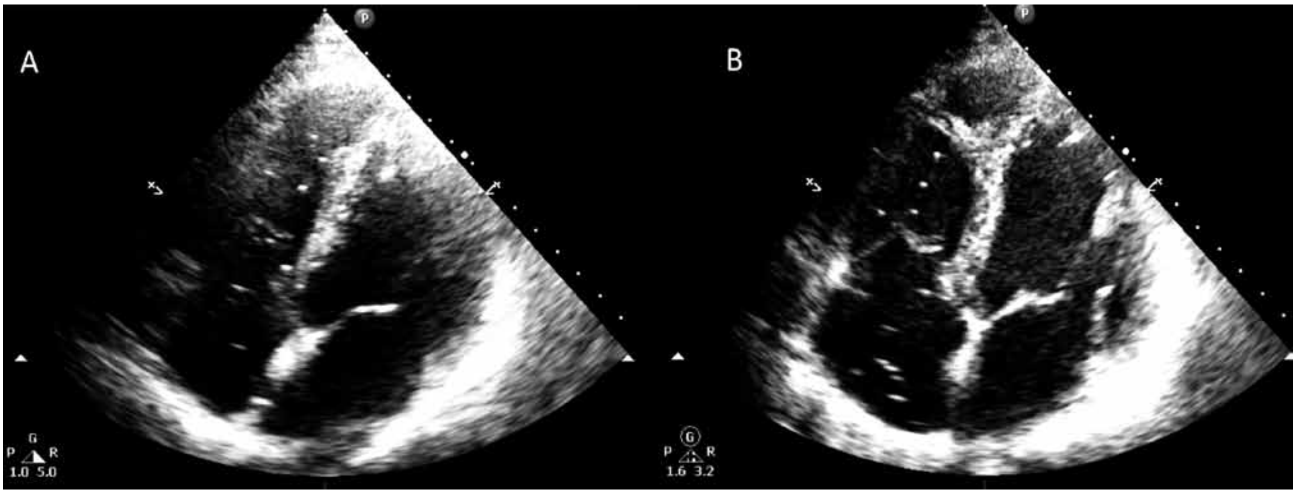
Of the 69 paired measurements, 54 matched; that is, both the harmonic and the conventional images were graded as the same on the EB scale. Of the 54 pairs that matched, 39 were of an EB grade of 3 or above (high grade), while 15 were graded at 2 or below (low grade). Of the 15 pairs that were not matched, 10 involved harmonic EB grades of 3 or above, while the remaining 5 pairs were mismatched when the harmonic EB grade was 2 or below. There was no significant difference in the frequency of the high/low grade split between matching and non-matching observations (matching low grade – 15, high grade – 39; mismatch low grade – 5, high grade – 10; Fisher's exact test, *P* = 0.45). However, in 14 of the 15 mismatched pairs, the score was higher when harmonics was used. In 10 of these observations, the use of harmonics translated the result from an EB < 3 to an EB > 3. In no case did the converse occur. The median mismatch in those 15 pairs was 1 (range -1 to 3) EB grade. It should be noted that in one subject, imaging was difficult; the quality of both the harmonic and particularly the conventional images made them difficult to score, and this subject accounted for a number of the mismatched pair grades.

Discussion

EXPERIMENTAL STUDY OF HARMONICS VERSUS CONVENTIONAL ULTRASOUND

In this study, 2D harmonic ultrasound images made post-decompression were compared with conventional ultrasound images, to reveal whether any extra bubble load information could be gained by using the former (Figure 2). It should be noted that the study may be limited by the use of a single machine; the effectiveness of harmonic and no-harmonic settings might differ between models used in decompression studies. Harmonic imaging is known to increase grayscale resolution, so improving the sharpness of the image. It should also have the capability to reveal

Figure 2
Comparison of a conventional 2D ultrasound image (A) with a harmonic 2D image (B); the images are from the same subject taken sequentially, so at a very similar time point; note the improved contrast of B and clarity of the structures and bubbles



smaller bubbles, should any be present, because of improved spatial resolution.

Over three-quarters of the paired images produced the same EB grades; and the only obvious difference was in the greyscale quality of the image; the images were much sharper and of greater contrast (Figure 2). Although there was no significant difference between the ratio of matching and non-matching pairs with low and high grades, a clear majority (14/15) of the non-matching pairs showed more bubbles when harmonics was used. In small samples and particularly if subjects are difficult to image clearly, there is a possibility that the harmonic technology will skew the results towards higher bubble grades. However, unless the median of the bubble grades is close to a given study cut-off point, for instance between grades 2 and 3, it is unlikely that the results will produce a significant difference between studies made using old or new ultrasound imaging technology.

Of the 54 grades that did match, 39 of these were of an EB grade of 3 or above, meaning that there was at least one bubble seen in every cardiac cycle. An EB grade 3 approximates to a KM III- or III on the KM Doppler scale and has been shown to carry a higher risk of DCS in comparison to KM grade II or below in a number of studies.[5,17,18] It is at this higher end of the grading scale that bubbles visible only with harmonics would be of importance. For example, it was the presence of high ultrasound grades in several studies that prompted the suggestion that harmonic ultrasound was raising reported grades with small bubbles that were previously invisible.[7,15] However, the present results show a good level of agreement at EB grade 3 or over and so would seem to refute that argument. Perhaps this should have been expected; it has been noted that harmonics may have additional sensitivity to bubbles with resonance close to the driving frequency of the device only, so very small bubbles would be detected only by medical grade equipment.[19]

In some cases, alternative explanations for unexpectedly high bubble loads might be relatively straightforward. Using the V-planner software and the VPM-B algorithm (variable permeability model – HHS Software Corp., Kingston, ON, Canada) to derive the dive profiles for trimix dives, large numbers of VGE and AGE were observed.[15] This may have been caused by the critical level of the algorithm being set too high and so, simply, more decompression was needed to reduce the bubble load and DCS risk. However, the large number of bubbles produced following the no-decompression dives was not expected, as those dive profiles were based on standardised and conventionally tested tables that were thought to be relatively conservative.[7,20]

The classical method of testing a dive table is to use DCS as a binomial yes/no endpoint. Interestingly, and as above, when ultrasound measurements have been made recently following such tabled dives, results suggest that they are often not as conservative as might have been expected. For example, the UK Royal Navy's Table 11 (their standard air diving table, based on Haldanian principles) has been used in a number of studies to test the effect of different prophylactic regimes on VGE production, as this table is known to be 'bubble producing'.[16,21,22] The resulting bubble grades usually range across the entire scale. Perhaps the occurrence of high VGE grades and occasional arterial bubbles when using traditionally tested dive tables is 'normal'. Is it simply the fact that ultrasound monitoring is now more common that makes us increasingly aware of their presence? That conventionally tested tables do appear safe in terms of DCS risk also further highlights the uncertain relationship between high bubble loads and DCS occurrence.

Although the majority of images did match in the present study, a 100% record was not observed. At low levels of bubbling, the inability to make simultaneous measurements will pose a disadvantage when trying to make comparisons. The mismatch in higher EB grades above 3, where at least one bubble must be present every cardiac cycle, is likely to be explained by the ability of harmonic imaging to improve resolution, particularly in those subjects where imaging of any kind is difficult owing to their individual anatomy. Clearly this is where harmonic technology could make a difference in post-decompression bubble monitoring.

TECHNICAL DISCUSSION: BUBBLE SIZE AND CONSEQUENCES

If bubbles detectable by harmonic ultrasound are not responsible for a perceived increase in bubble loads, it does not mean that gaining an impression of the size distribution of decompression bubbles is not still of use. Indeed, one aspect of imaging that may aid in investigating the aetiology of DCS is the increasing ability to gain a quantitative measure of the size of the bubbles present. Knowing the distribution in size of intravascular bubbles is desirable, as size plays an important part in how far a single bubble can travel in the arterial system.[23] Those bubbles with the smallest radii have the shortest lifespan. If passing from the venous to the arterial circulation, they will immediately become subject to higher mechanical pressures that should mean that they are crushed very swiftly.[24] The suggestion has also been made that arterial bubbles usually have venous origins, in which case the lung would act as a filter for bubbles over a certain size.[23]

The approximate diameter of a pulmonary capillary is around 10 µm.[25] Bubbles of this diameter or less can cross the lung under ‘normal’ conditions. Should any of these very small bubbles be present and cross to the arterial circulation, they would likely collapse quickly. Indeed the majority of VGE reaching the lungs are excreted to the atmosphere by molecular diffusion across the arteriolar wall into the alveolar spaces, where the rate of washout is related to the mean pulmonary artery pressure and right ventricular performance.[26,27] It is during adverse conditions, such as emergency surfacing or surface recompression for example, that problems might occur. In the presence of large VGE loads (KM grades III and above) or under the influence of other factors that can combine with VGE load, the pulmonary capillary filter might be overwhelmed. Larger bubbles may deform and elongate to pass through to the arterial circulation, while smaller bubbles might find conditions that would allow them to grow, perhaps then leading to neurological DCS.[24,28] So the ability to assess both bubble size and bubble load with ultrasound would be beneficial in terms of gauging DCS risk.

Doppler cannot make a quantitative assessment of bubble size, although technically it has been found that the amplitude of the reflected signal could be considered approximately proportional to the radius of the bubble, so a qualitative assessment of bubble size could be derived.[29] It is not possible with ultrasound imaging to assess absolute bubble size using either conventional or harmonic technology, although a relative idea of size may be gained. However, recently developed dual-frequency technology may allow us to accurately size bubbles in the future.[30] The dual frequency device emits a ‘pump’ and an image ‘signal’ at two frequencies. The pump signal causes appropriately sized bubbles to resonate, so that when the image signal hits a resonating bubble, a ‘mixing’ signal is returned. A study in swine has shown that such mixing signals can be detected in the right atrium and histograms of estimated bubble sizes produced from the data, while stationary bubbles may also be monitored in the tissue post decompression.[30–32] This may lead to a new understanding of bubble evolution and another method through which to evaluate DCS at multiple sites around the body, once the technology becomes more commonplace.

At normal pressure, conventional 2D ultrasound has been reported to be able to detect bubbles in vivo at a diameter with a lower limit of 10 to 20 µm although, if packed together closely, groups of bubbles may be identified as one large bubble.[33] Noise in the images will also influence detection. The size of the bubble detected is dependent on the operating frequency of the probe used; usual transmitted frequencies range from 1 to 10 MHz, where 1–3 MHz is used in the heart and 5–10 MHz is used in smaller vessels closer to the surface of the body.

The lower limit of detection for Doppler will be higher than that of 2D imaging. In vitro studies have shown that bubbles of a minimum 30 µm in diameter could be detected by a 2 MHz probe in the presence of red blood cells flowing through a 9.6 mm diameter cannula though, in vivo, the minimal detectable size might be larger.[34] In the pulmonary artery or right ventricle for example, where the volumes of blood present are far greater, only signals from larger bubbles may be great enough to overcome the higher background scattering signal produced by the millions of red blood cells present.[34] Overall, Doppler is limited by its inability to detect bubbles below a certain threshold.[3] This is determined by a number of factors including driving frequency, transducer configuration and the scattering properties of the moving objects in the ultrasonic field (red blood cells and bubbles) that are needed to produce a Doppler shift. So, is Doppler able to give a relatively complete representation of bubble load following decompression in humans?

In a study of the size distribution of intravenous bubbles formed by severe decompression in the dog, it was found that they ranged in size from 19–700 µm in diameter, so above the size that could normally pass through the pulmonary filter.[23] At five minutes post decompression, most bubbles measured between 24–32 µm, with the size increasing with time to range from 50 to 170 µm at 35 minutes. The measurements were made by drawing venous bubbles from the dog through a cannula, so the range of bubble sizes may have been altered and not be completely reflective of in vivo bubble distribution. In theory, Doppler measurements made using a 2 MHz probe should be able to report the majority of the bubbles in this range. However, at the onset of bubbling, when it would seem that smaller bubbles are produced, it might not be possible to report the entire bubble load over the entire period of bubble evolution. Nevertheless, if these results from the dog could equate to humans, then Doppler should be able to describe a relatively complete illustration of post-decompression bubble load in the diver.

It may be that bubbles small enough to pass the pulmonary capillary bed filter (< 10 µm) without deformation are relatively uncommon. However, arterial bubbles are now reported in studies more frequently than might be expected.[7,15] This observation poses a number of questions, not least whether the subjects in these studies represent a group particularly predisposed to arterial bubble production by their environment, lifestyle or physiology, e.g., the presence of a patent foramen ovale (PFO). Perhaps the most important question is why are these bubbles being produced and what is their level of pathophysiological risk? This question is pertinent as, globally, DCS incidence rates remain low at around 0.03% (derived from a sample of 135,000 dives made by 9,000 divers).[35]

Historically, the observation or awareness of arterial gas bubbles has always created apprehension, as they may potentially lodge, sludge and then grow in the arterial blood supply to organs and tissues, particularly the brain and spinal cord. For example, in a paper on Doppler ultrasound for monitoring haemodynamic changes and bubbles, it was noted that a large number of bubbles were found in the aorta and carotid artery of the human subjects, but no signs of serious DCS accompanied them.[36] At the time (early 1980s), these findings were met with general disbelief and concern, prompting a lively discussion. Today, the role of arterial bubbles in the onset of DCS remains unresolved.

VGE LOADS: THE ASSOCIATED RISK OF DCS AND AGE DEVELOPMENT

In the KM grading system, the highest VGE load is represented by grade IV (Table 1); a signal given this grade indicates that individual bubble sounds cannot be differentiated; instead a continuous sound is heard in 100% of heartbeats and is clearly perceptible against the cardiac blood flow. A KM grade IV is equivalent to an EB grade 5; Figure 1 depicts the huge bubble load associated with these grades. Of the 1,726 human air dives where Doppler data were collected during a safe dive limits survey, only three precordial KM IV grades were recorded at rest.[37] There was no concomitant DCS in these subjects. It should be noted that in controlled experimental diving trials, when a subject presents with DCS, he is usually then lost to Doppler monitoring as medical treatment commences and takes precedence over further measurements. Therefore, it becomes impossible to determine what the maximum bubble grade might have been, should monitoring have been able to continue. If, for example, symptoms appeared before the first measurement was made, the subject may well have had very high bubble grades (Nishi R, personal communication, 2014). KM III grades were more common (191) and of these, 21 subjects had symptoms of DCS (11% incidence). In total, 35 subjects were reported to have DCS, giving an overall incidence rate of 2% from 1,726 dives. That such a small number of maximal bubble grades and cases of DCS were observed indicates that the dives performed in this study had adequate decompression.

However, when maximal grades are provoked by more extreme dive profiles, it seems the risk of DCS is raised. In an early study, five of 174 participants had Spencer grade IV bubbles (equivalent to KM grade IV) and, of these five, four developed DCS.[6] Some of these dives were extremely provocative and outside of normally accepted limits. This is again reflected by the fact that in the same study, of 14 subjects with grade III scores, six (vs. 21 of 191 [11%] in the previous study[37]) developed DCS. In another study, also using ‘higher risk’ dives, six cases of DCS were observed from 19 subjects with grade IV bubbles.[38] Although the relationship between bubble grade and DCS occurrence is not clearly defined, it is probable that there is an increased risk for DCS with higher bubble grades (III and IV). Of course not all DCS will be reported and bubble grading is subjective, so some latitude must be given to these comparisons.

The standard treatment for DCS is recompression. Altitude exposure studies are often allowed to progress until DCS occurs, with the subject then simply being recompressed to normal atmospheric pressure to resolve the problem, unless severe symptoms require further hyperbaric treatment. Thus, hypobaric studies may help to define the relationship between very high bubble grades and DCS, as grade IV scores occur more often. In a study investigating VGE as a predictive measure of hypobaric DCS, 121 of 249 subjects with grade IV scores developed DCS (49%), while in another, DCS presented in 391 of 633 subjects with grade IV scores (62%).[4,39] However, in describing this relationship, the differences between hyperbaric and hypobaric exposure should be considered. During hypobaric exposure, grade IV scores may persist for some time before DCS symptoms occur. In hyperbaric studies, where bubbling is usually measured post decompression, the bubble load might fall away from grade IV before the onset of symptoms, and this might also be true during altitude exposures. The duration of high levels of bubbling may determine if and when DCS occurs, influencing the mode or type of DCS that develops. For example, it is thought that neurological DCS is closely linked to high bubble loads immediately post dive, while limb bends are associated with more prolonged bubbling.[40]

Another consideration when assessing bubble data obtained with both Doppler and 2D ultrasound is that the precordial site (cardiac) is not always the most effective in which to monitor VGE. Although less fashionable, it is acknowledged that bubbles may be heard with Doppler in the subclavian vein when they are not obvious in the precordial area. This is because of the diminished background noise at this site; in the heart, noise is ever present, created by the valves, heart wall and greater blood flow, all of which mask the signal. In the safe dive limits survey study mentioned earlier, seven subjects with zero precordial bubble grades presented with DCS.[5,17] However, when subclavian measurements were taken into account, these subjects were seen to have bubbles. If no subclavian bubbles were present, no cases of DCS were seen ($n = 819$). So this study, the largest of its kind, demonstrated that DCS was always accompanied by VGE when both precordial and subclavian measurements were taken into account. This presents a good argument for both sites to be measured as a standard. It also illustrates that methodology and protocol play an important role when considering and comparing data, particularly from different laboratories, as measurements may have been made, for instance, with varying frequency or from different sites.

If the magnitude of the bubble load post decompression is important with respect to the development of arterial gas emboli, then the risk of bubbles passing to the left heart is further heightened in some people owing to the presence of a right–to-left shunt across a PFO. Approximately 25–30% of the population, irrespective of gender, have these well documented, inter-atrial communications that persist after birth.[41] PFO may vary greatly in size from person to person and in certain circumstances, including the high pressures created by large amounts of venous gas in the right heart, which may lead to right-to-left shunting of blood.[41–43] When VGE move across the septum, the arterial circulation will become victim to embolization. Scanning for PFO is not routinely performed for commercial, military or recreational divers, as the associated risk of DCS derived from the condition is relatively low. The mean estimated incidence of neurological DCS (Type II) is 2.28 cases per 10,000 dives across the diving population, while the odds ratio increases only 2.5 times in divers with a PFO.[44]

A more recent study found the risk of serious DCS in subjects with a PFO was more than five times that without PFO and the severity of the DCS increased in parallel with the size of the PFO.[45]

As divers have a one-in-three risk of having a PFO and an even higher chance of producing venous bubbles following a normal, incident-free air dive, it is very likely that at some point during their diving career, contributing factors such as repetitive diving, environment, health issues, high-risk dive profiles or dive accidents will provoke a large bubble load to form and they may be exposed to arterial gas bubbles. The aforementioned Norwegian study is evidence of this: five out of 12 divers performing successful no-decompression air dives exhibited arterial bubbles upon 2D ultrasound monitoring post dive.[7] The results of that study were unexpected, as the Norwegian no-decompression tables used were thought to be relatively conservative.[20] Arterial bubbles were also present in five out of seven subjects, and nine out of 21 dives, following trimix profiles calculated using V-planner, and they have also been observed following heliox saturation dives from 300 and 250 msw.[15,46] In all of these cases, there was a concomitant high level of bubbles present in the right heart, but importantly, no clinical symptoms or signs of DCS.

It is probably because of the increasing use of 2D visual ultrasound, allowing us a view of all four chambers of the heart, that we are becoming more aware of such unexpectedly high left-heart bubble loads. How they should be approached, in terms of risk of DCS and the subsequent management of divers, remains speculative. Perhaps a cautious attitude would still be recommended, despite our increasing awareness of their presence and relatively low worldwide DCS incidence.

Given that the detection of bubbles is now easier to carry out, present and future technology should provide us with more information on the size and load of bubbles in both the venous and arterial circulations. This will be helpful in exploring the links with and determining the risks of DCS. Moreover, as the increased observation of arterial bubbles has not gone hand in hand with an increase in DCS, future advances in technology should help us understand further the mechanics of bubble formation and then to unravel their role in initiating DCS.

Conclusions

Doppler ultrasound remains a useful tool for decompression research although it is constrained by the difficulty of training operators and its limited window of observation. Portable, more affordable user-friendly ultrasound imaging units have become more widely used in diving research; this might help to explain the seemingly increased observation of VGE and left-heart bubble loads. Unlike Doppler, 2D imaging allows us to view both sides of the heart concurrently, which may explain the apparent increase in incidence of observations of left-heart and arterial bubbles. However, there has not been a concomitant increase in the incidence of DCS. If the frequent occurrence of low numbers of left heart bubbles is 'normal', should this change our perception of their importance to the risk of DCS?

Harmonic technology does not seem to have altered findings relating to post-decompression bubble loads as some have postulated; our study found a good level of agreement between the grades of images made with both conventional and harmonic imaging technology. Thus, for the most part, harmonic imaging does not seem to impart any fundamental benefit in terms of improving the detection of decompression bubbles or conventional grading of such bubbles. However, the present study did not find a 100% match between harmonic and conventional images. This deficit is most apparent in a subject whose heart is difficult to scan. It is in these cases that the most benefit can be gained by technological improvements: bubbles that might have been missed can often be observed using harmonics, because of the improved resolution it affords. For this reason, harmonic technology does make imaging easier overall and helps to improve the accuracy of grading.

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The database of randomised controlled trials in hyperbaric medicine maintained by Michael Bennett and his colleagues at the Prince of Wales Hospital Diving and Hyperbaric Medicine Unit, Sydney is at:
<http://hboevidence.unsw.wikispaces.net/>

Assistance from interested physicians in preparing critical appraisals is welcomed, indeed needed, as there is a considerable backlog. Guidance on completing a CAT is provided. Contact Associate Professor Michael Bennett: <M.Bennett@unsw.edu.au>