BUBBLE MEASUREMENT TECHNIQUES

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Take home message

- Ultrasonic techniques allow the visualisation of microbubbles in the heart and blood vessels after diving
- Techniques to detect bubbles include Continuous Wave Doppler, Transthoracic Echocardiography, Pulsed Doppler Detection, and Transesophageal Echocardiography
- Counting and grading the amount of bubbles following diving is a powerful tool to validate current dive tables and algorithms, assess the effect of different preconditioning techniques, and therefore increase diving safety
- There are different counting and scoring scales to categorize bubble quantities
- Although useful for research applications, counting bubbles has its limitations in clinical application and therefore doubtable diagnostic value for the individual DCS risk assessment.

Abstract

Nitrogen desaturation in SCUBA divers leads to the production of circulating gas bubbles during the decompression period and over the ensuing minutes. Since the 1970s and the studies of Guillerm and Masurel in France, and Smith and Spencer in USA, these bubbles have been detected using ultrasonographic techniques. A system of classification to assess the quantity of circulating bubbles has been developed by several research groups. The bubble scores or scales are based on the number of bubbles with respect to the cardiac cycle, commonly referred to as heartbeat. Several studies have investigated the correlation between the bubble rating and the probability of a decompression accident. Although the significance of this correlation is debated, all of these studies agree that the risk of DCI is low in the absence of circulating bubbles. Bubble screening can therefore mainly be used as a safety indicator for validating diving profiles. A decompression profile that does not induce the production of bubbles in a large population of divers may be considered a safe profile. The main quality of a bubble screening procedure is therefore its sensitivity. On the other hand,

echo techniques have a low specificity to predict DCS. Indeed circulating bubbles are frequently observed after diving in subjects without any resulting clinical disorders. In this respect, in addition to avoiding DCS, the aim here is to limiting decompression stress evaluated against circulating bubbles post dive imaged using ultrasound. The aim of this chapter is to discuss various techniques used to screen circulating bubbles, their applications, and their limitations.

1. Ultrasonographic techniques used to screen for circulatory bubbles

Ultrasonographic techniques are also widely referred to as ultrasound, sono, echography or simply echo. The idea behind this method is to use high frequency sound waves and their echoes to locate and display organs or tissues in the human body. This technique is comparable to SONAR used in submarines or the echolocation of whales. The frequencies used in medical diagnostics, treatment and follow-up of patients are ultrasounds, ranging between 2 and 18MHz (sounds above the threshold of human hearing) depending on the target organ or tissue. The following techniques have been proved suitable to screen circulating bubbles following a dive.

1.1. Continuous Wave Doppler (CW Doppler)

Continuous Wave Doppler with ñblindò positioning of the transducer (i.e. without ñseeingò the blood vessel over which the probe is placed) was the first method used to screen circulating bubbles. This procedure has been extensively studied in the 70's by Spencer. The signal is recorded as an audio-file, which can then be evaluated by different observers. Several anatomical sites can be explored including the pulmonary artery, subclavian vein, and the lower vena cava. The pulmonary artery outflow tract is the most appropriate site for studying bubble quantities induced by a dive, as all of the venous blood passes here. The studies of Spencer, Kisman and Masurel using the Doppler effect resulted in classification systems for quantifying the circulating bubbles (see **Table 1 and 2**). The bubble grades rate the number and frequency of bubbles compared with the heartbeat. The Kisman-Masurel code is somewhat more complicated than the Spencer scale, as it is composed of three parameters (frequency, loudness, duration) in various combinations (see **Table 2**). However, a ñconversionò scale from KM code to Spencer scale has been developed. The limitation of CW Doppler is the bubble detection sensitivity (diameter of detectable bubbles) and the fact that it takes a lot of training to interpret the bubble signals correctly. Therefore, there may be a variation in results according to the experience of the observer. Consequently, interpretation of statistical results, especially when comparing several series, must be taken with caution.

GRADE	Auditory Assessment of Continous Wave Doppler Recordings
Grade 0	Complete lack of bubble signals
Grade 1	Occasional bubble signals, the great majority of cardiac cycles are free of bubble signals
Grade 2	Many, but less than half of the cardiac cycles contain bubble signals, singly or in groups.
Grade 3	All of the cardiac cycles contain bubble signals, but not overriding the cardiac signals.
Grade 4	Bubble signals sounding continuously throughout systole and diastole of every cardiac cycle, and overriding the normal cardiac signals.

Table 1. Grading with the Spencer scale (first established in 1974)

CODE	**FREQUENCY** Bubbles per cardiac cycle	**PERCENTAGE** Cardiac cycles at rest	**DURATION** Movement, duration cardiac cycles	**AMPLITUDE**
0	0	0	0	No bubbles discernible
1	1-2	1-10	1-2	Barely perceptible
2	Several, 3-8	10-50	3-5	Moderate amplitude

3	Rolling, 9+	50-99	6-10	Loud
4	Continuous sound	100	10+	Maximal

Table 2. Kisman-Masurel code (originally published in 1983)

1.2. Transthoracic echocardiography (TTE)

Transthoracic echocardiography is a good tool for screening and viewing circulating bubbles in the heart chambers. Gas bubbles appear as high intensity blobs on the images. 2D echocardiography is currently the most frequently used modality for screening circulating bubbles. Images can be obtained from the parasternal view (long axis and short axis of the heart) while the diver is lying on his left side (see below), and from an apical four chamber view (**Figure 1 and 2**), where the diver is lying on his back. These recordings can be performed at rest, during movement, or during a contraction of the quadriceps or other big muscles to dislodge bubbles that did remain stuck at blood vessel walls and then start circulating.

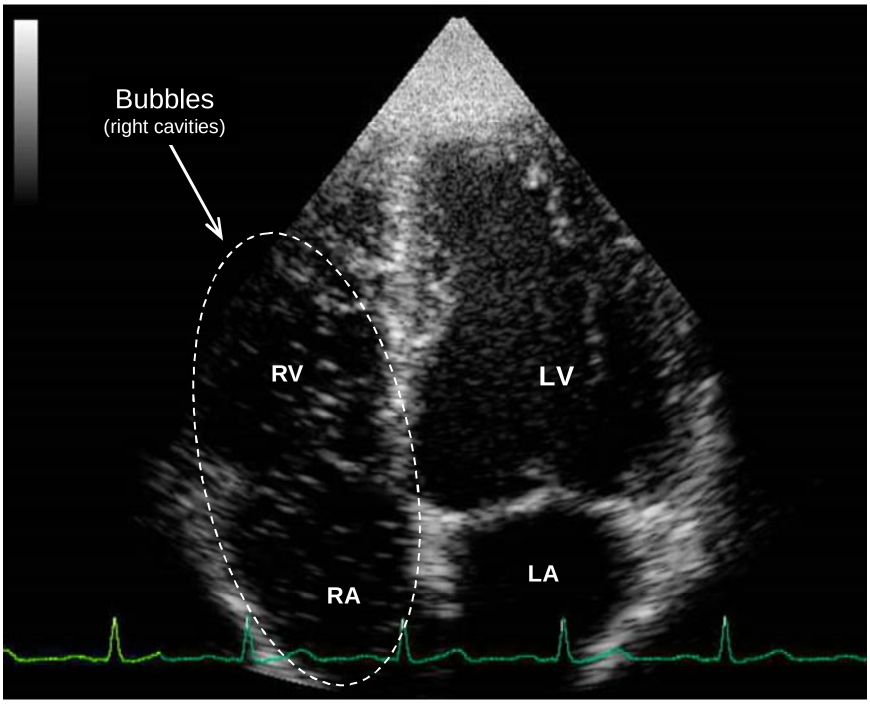

Figure 1. Apical four chamber view: Circulating bubbles in the right cavities of the heart (note: ultrasonic recordings result in a mirror inversion of right and left side of the heart)

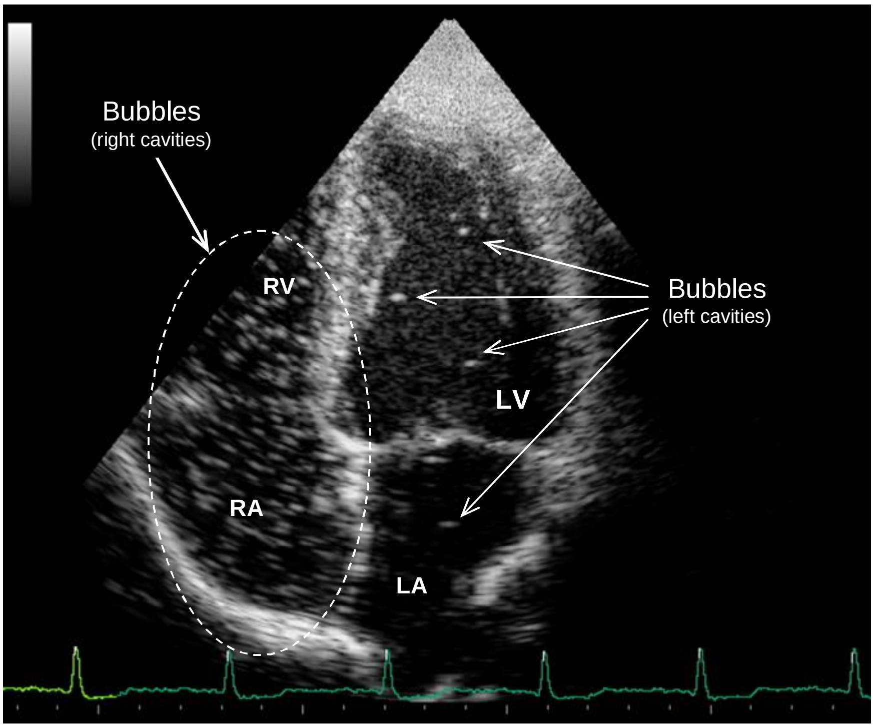

Figure 2. Apical four chamber view: Circulating bubbles in the right cardiac cavities with passage in the left cavities

In 2007, Brubakk & Eftedal have proposed and validated a scoring scale which is easily learned and executed (**Table 3**).

GRADE	Visual Observation in Echocardiograph Recordings (Images)
Grade 0	No observable bubbles
Grade 1	Occasional bubbles
Grade 2	At least 1 bubble every 4 cardiac cycles
Grade 3	At least 1 bubble every cardiac cycle

Grade 4	At least 1 bubble per cm^2 in every image
Grade 5	ñWhite-outò, single bubbles cannot be discriminated

Table 3. Brubakk & Eftedal scale (2007)

Very recently, a new counting method was developed and validated by Germonpre et al. (2014) whereby actual bubble signals are counted in standardised TTE image sequences. This method permits to average bubble signals in the right heart cavities over 10-15 heartbeats, analysing only a few frames per heartbeat (just before the contraction of the right ventricle, see **Figure 3**). The result is a quantitative, not a categorized figure which may be used to evaluate decompression stress in medium-to-low bubble dives, with very good agreement between raters even for non-medical personnel. Although this technique requires a rigorous fixed echocardiographic visualisation and is thus more difficult to learn than a ñstandardò 2D evaluation, it opens the possibility for automatic ñbubble countingò by intelligent computer learning algorithms. These are actually in development showing as good an agreement with humans as human to human raters on the same videos as the Germonpre et al. 2014 and will permit the continuous counting of bubbles in a one to 2 hour period after a dive. Integration of the counted bubbles would then become a useful tool for evaluation of the ñdecompression stressò and the influence of a modified dive profile or of a pre-dive intervention (pre-conditioning).

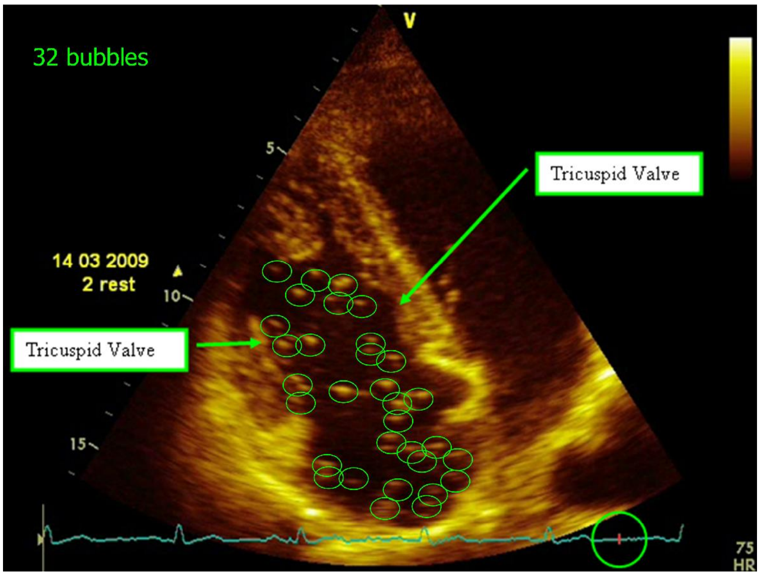

Figure 3. Frame-based bubble counting (artificial gold colouring used to improved contrast). Manual counting, bubbles outlined in green.

1.3. Pulsed Wave Doppler detection

Circulating bubbles can also be detected using the so-called pulsed-wave (PW) Doppler effect. It is based on the same technique as the CW Doppler, but the probe will not send a constant signal (continuous wave) but intermitted signals (pulsed) whose echoes are then recorded back. Both techniques have different applications in diagnostics. The transducer can be positioned in a blind manner and the investigation methods are similar to those described for continuous wave Doppler. Furthermore, two-dimensional echocardiography can be used to guide the Pulsed Doppler study of the pulmonary artery blood flow (**Figure 4**).

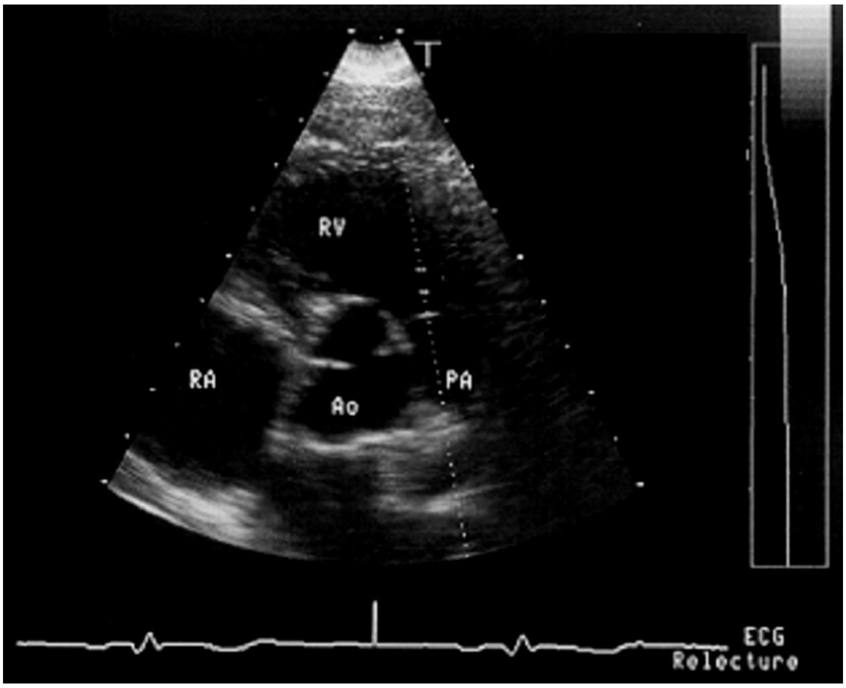

Figure 4. Parasternal short axis view: study of pulmonary blood flow by pulsed Doppler. The sample volume (between the two markers on the dotted line) is placed in the outflow area of the right ventricle just below the pulmonary valve. Ao: Aorta, RA: Right atrium, RV: Right ventricle, PA: Pulmonary artery

The sample volume is placed in the outflow area of the right ventricle. Circulating bubbles are visualized in the flow spectrum as bright spots (**Figure 5 and 6**). A specific echocardiographic and pulsed Doppler bubble grade scale has been derived from the scales of Spencer (**Table 4**).

Grade 0	No detectable bubble signal (2D echocardiography and pulsed Doppler ultrasonography)
Grade 1	Occasional bubbles; the great majority of cardiac cycles are free of bubbles (2D echocardiography and pulsed Doppler ultrasonography)
Grade 2	Flow of bubbles (2D echocardiography); many but less than half of the cardiac periods contain bubble signals singularly or in group (pulsed Doppler ultrasonography)
Grade 3	Flow of bubbles (2D echocardiography); the majority of the cardiac periods contain bubble signals singularly or in group (pulsed Doppler ultrasonography)
Grade 4	Bubbles fill cardiac chambers (2D echocardiography); all the cardiac periods contain bubble signals in group (pulsed Doppler ultrasonography)

Table 4. 2D Echocardiographic and Pulsed Doppler Grade (Boussuges 1998)

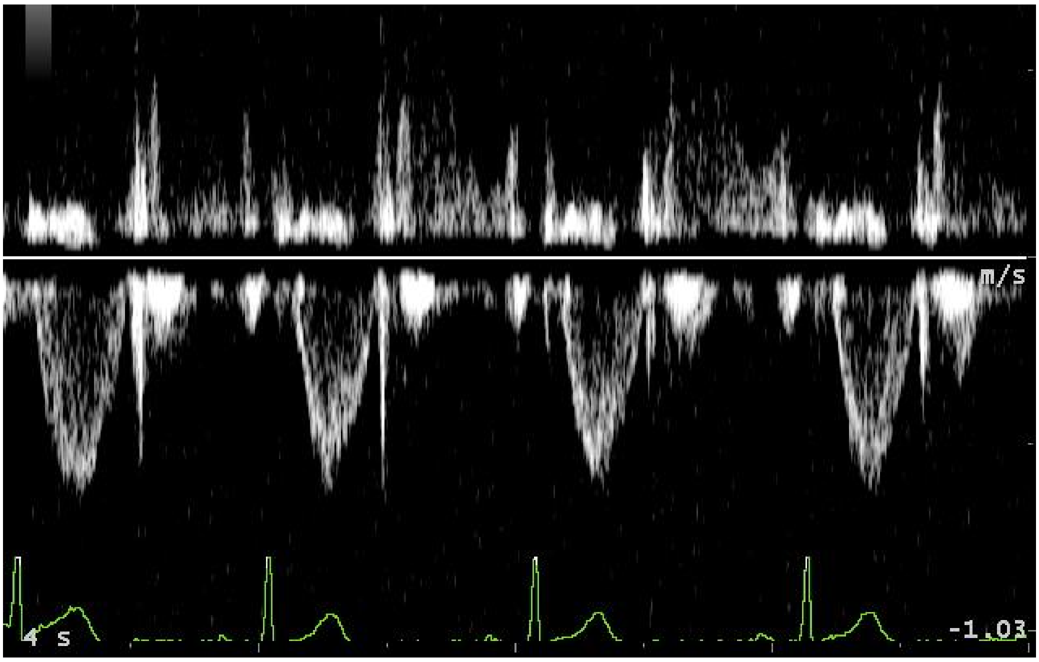

Figure 5 Normal pulmonary blood flow as shown by PW Doppler

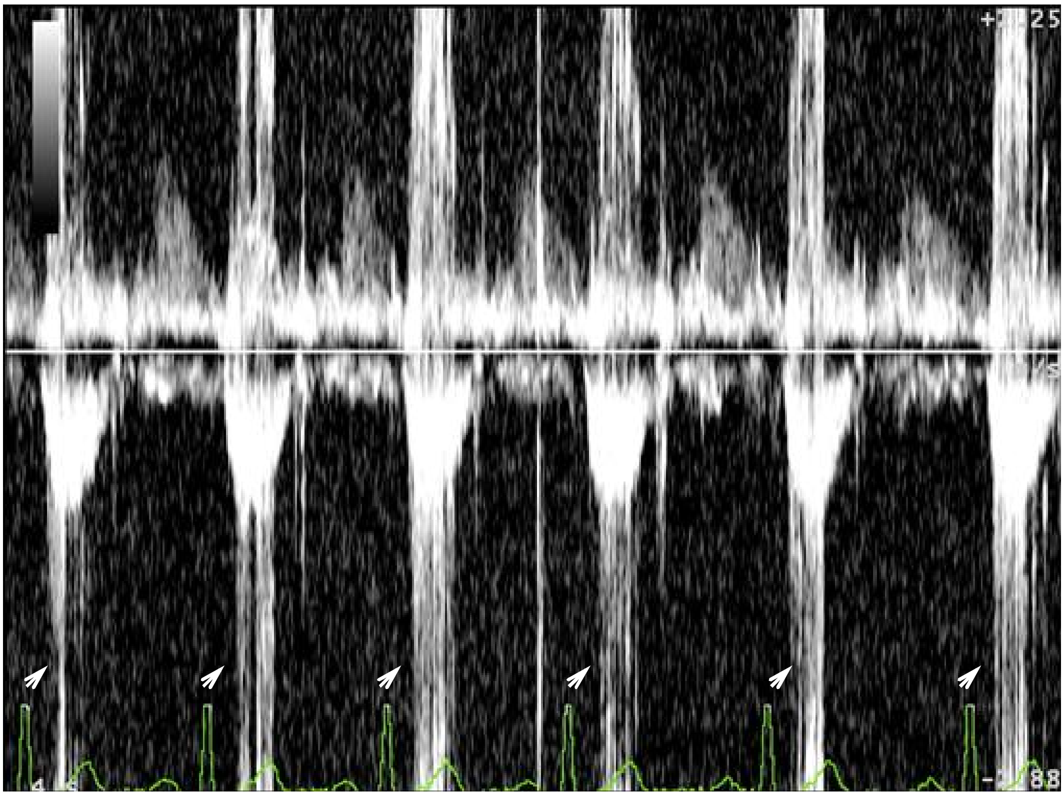

Figure 6 Circulating bubbles detected in the pulmonary blood flow: the arrows indicate bubble signals in each cycle overriding the pulmonary blood flow

1.4. Transoesophageal echocardiography (TOE, *am. engl. TEE)*

Transoesophageal 2D mode ultrasonography is a so-called ñinvasiveò procedure in which the transducer is inserted into the mouth and oesophagus of the subject (Figure 7). The image is generally more accurate than transthoracic echography because of very limited tissue interference between the transducer and the heart; in the latter, ribs and chest muscles produce artefacts and the cardiac structures are much more distant from the probe. Some major limitations of the transoesophagal imaging are that it is uncomfortable and more time consuming than non-invasive techniques, it needs medical personnel on site and requires the subject not to eat or drink several hours before the screening. Although it has been shown to be useful in screening bubbles, its actual use is thus limited to experimental protocols in anaesthetised animals.

Figure 7. Possible Positioning of the transducer for TTE: apical view (A) and parasternal view (B) and Transesophagal echocardiography (C)

2. Comparative studies

Some studies have compared the various techniques established to screen circulating bubbles. Norwegian scientists for instance found that researchers would come to the same conclusion on the quantity of circulating bubbles in the image grading system for 2D echocardiography and the Spencer code for Doppler signals in resting subjects. However the results between the two techniques derived strongly from one another if the screening was done on moving subjects. In divers with poor quality imaging (due to movement or body composition), 2D ultrasonography and Doppler methods can be considered as complementary. It has been reported that pulsed Doppler guided by 2D imaging is the superior method for the detection of venous gas emboli compared to 2D echocardiography alone. In a comparison of CW Doppler with blind positioning of the transducer and pulsed Doppler guided by 2D-echocardiography, both methods were found to be equivalent in terms of sensitivity when the ultrasound exploration is easy to perform and yields a good Doppler signal (i.e. in young athletic divers). In cases where the examination is more difficult to perform, 2D images guided by pulsed Doppler are more precise. Using imaging to guide the pulsed wave Doppler facilitates good quality recordings of the blood flow in the pulmonary artery and optimizes the screening procedure for circulating bubbles.

3. Application of circulating bubble screening-recommendations, interest, limitations

After a dive, the desaturation process may last several hours with an *estimated* maximum rate of circulating bubble detection occurring around 30-40 minutes after surfacing. Continuous or repeated detections performed at intervals every few minutes are needed to estimate the whole bubble quantity and maximal bubble grade. Furthermore, circulating bubble grade may vary over a very short time frame. An automated assessment method based on detecting and counting bubbles in real time would assist analysis and advances in this field are on-going. Recordings must not exceed one minute in a resting diver to limit bias caused by the subject or the examiner. It is known that circulating bubbles can sometimes pass into the arterial circulation via a right-to-left shunt, such as the inter-atrial PFO or pulmonary shunts. Consequently, an apical four-chamber view (see **Figure 1 and 2**) and/or aortic blood flow recording should be systematically performed to detect circulating bubbles in the left (arterial) cavities. To improve the significance of the findings, the standard protocol is to record the explorations as a video file for later analysis by two independent investigators. Bubble grades provide only a semi-quantitative evaluation of the number of bubbles due to the categorical nature of the data. This means for example grade 2 does not necessarily show twice as many bubbles as grade 1 and bubbles do not appear regularly in respect to time interval and quantity. Because of these limitations, a sort of linearization such as the Kisman Integrated Severity Score (KISS) has been proposed, where the results of three or four measurements at various time intervals are integrated into a single number. These mathematical methods facilitate the statistical treatment of these data but it should be kept in mind that they only provide an estimate of the circulating bubble production.

Since the 80ȏs, there have been quite a few studies that reported a correlation between detected bubble quantity and DCS. Maximal observed bubble grade has also been considered as an estimate for decompression stress. The interpretations of these studies are debated because correlations between high bubble grade and DCS risk are more frequently based on dry hyperbaric chamber dives and less frequently on real open sea diving. Furthermore, the clinical disorders reported in the chamber are articular pain or cutaneous manifestations and the incidence of these disorders seems to be particularly elevated in comparison with real SCUBA diving. Finally, high bubble grades (bubbles throughout the cardiac cycle) are frequently observed in SCUBA divers showing no clinical symptoms of DCS; and perhaps even more astonishing are recordings from asymptomatic divers which clearly show bubbles in the left cavities. On the other hand, when few bubbles are detected during the whole desaturation period, the risk of DCS seems to be low but not nil. Limits of the interpretation of circulating bubble detection are also supported by the studies in altitude chambers. Indeed, women formed fewer nitrogen bubbles than men for a given exposure, but still seemed to have a higher incidence of altitude decompression sickness.

These observations indicate that although bubbles are commonly considered to be the trigger of DCS, some clinical manifestations of DCS are secondary to non-circulating tissue bubbles, are often related to inflammation and it is yet not completely understood which observations linked to decompression stress are caused by, and which are independent of (detectable) bubbles. Therefore, in an individual case of a diver with symptoms, detection or not of circulating bubbles has no real diagnostic value.

Conclusions

Circulating bubble detection provides a valuable tool for evaluation of the safety of a dive profile in a large population. Calculating the time integral of bubbles during the whole post-dive observation period would give an estimate of the total volume of intravascular gas. For a large population, when few bubbles are detected the dive profile can be considered safe. On the other hand, the use of circulating bubble detection in individual decompression stress or DCS risk in small populations is debatable. As detection techniques for circulating bubbles are getting more and more technologically advanced, these conclusions may (or may not) change in the future.

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