Original articles

Agreement of precordial and subclavian Doppler ultrasound venous gas emboli grades in a large diving data set

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Abstract
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Introduction: Doppler ultrasound is used to detect inert gas bubbles in the body following decompression from dives. Two sites may be monitored, the precordial (PC) and subclavian (SC) positions. PC is the predominant site, allowing observation of bubbles returning from the entire body. However, the SC site provides unambiguous signals, whereas the PC site is noisy and difficult to grade. This retrospective study compared agreement of PC and SC Doppler data.

Methods: Datasets from the large University of California at San Diego Doppler database were graded on the Kisman Masurel (KM) scale and included: one PC measurement at rest followed by three during movement ($n = 4$ measurements); this was repeated for the left ($n = 4$ measurements) and right ($n = 4$ measurements) SC veins, producing a set of 12 grades. Primary analysis included: agreement between resting PC and SC grades, between movement PC and SC grades, and for unmatched grades, whether the SC grade was higher or lower than PC.

Results: Four-hundred and fifty-three datasets were available (5,436 individual recordings). At rest, 281 (62.0%) PC and SC grades matched (weighted kappa agreement 0.33, 95% CI ± 0.04), while only 176 (38.9%) movement grades matched (0.29, ± 0.02). Of the unmatched data, resting SC grades were higher than PC in 70.3% and lower in 29.6%; after movement, SC grades were higher in 45.8% and lower in 54.2%.

Conclusions: These data revealed a large discrepancy between PC and SC grades. Overall, this suggests that Doppler observations from both positions will give the most comprehensive representation of bubble load.

Introduction

Decompression sickness (DCS) is thought to arise due to the formation and growth of inert gas bubbles from supersaturated blood and tissues during or after decompression. For many years Doppler audio ultrasound monitoring has been used to detect moving venous bubbles (often referred to as venous gas emboli [VGE]) and thereby derive a measure of 'decompression stress' following a dive, i.e., how likely it is that DCS might develop.[1] This technique uses a transducer to transmit sound waves into the body, with the resulting echo allowing determination of moving objects in the blood vessels and heart. Bubbles interact strongly with sound waves and so can be detected by this method.[1] In large datasets it has been observed that the higher the number of bubbles, or 'bubble load', the greater the correlation with the incidence of DCS;[1] therefore, a reliable measure of bubble load, such as Doppler monitoring, is of great use in scientific diving studies.

Doppler monitoring for diving research generally takes place at two positions on the body. In the precordial (PC) site the probe is positioned over the heart and more specifically, over the right ventricle and pulmonary artery, thus measuring the blood that comes back to the heart from the whole body.[1] The second position is over the subclavian (SC) veins that are positioned under the clavicle on both the left and right shoulders. These veins return blood to the heart from the upper body only and are not representative of the whole. However, they do have the advantage of providing an unambiguous signal, as bubble sounds in the SC vein are very distinctive against the quiet venous blood flow sound.[1] Bubbles monitored in the precordium can be difficult to differentiate from the turbulent sound of the heart, so grading them accurately can be problematic, particularly for inexperienced graders. In addition, varying anatomy, for example in a person with a very deep chest, can make it hard to hear clear heart sounds. Given these factors, it is apparent that PC and SC Doppler grades have the potential to be substantially different.

At the advent of the technique, it was recommended that both sites should be monitored following a dive and it was found that this appeared to improve the relationship between bubble load and DCS given that on occasion, no bubbles could be observed in the precordium but were apparent in the SC veins.[1] The most recent consensus on ultrasound measurements in diving research recommended that the PC site should be used as standard, with SC monitoring useful in providing additional information.[2] Generally, because the SC position does not report whole body venous return, this has led to the PC site becoming preferable in studies and often monitored alone. One retrospective study has compared resting only PC and SC Doppler data with respect to the probability of DCS (pDCS) associated with high bubble grades.[3] It found a high level of correlation between SC and PC resting grades (R = 0.66) and pDCS increased with increasing grade. They also noted that the DCS risk ratio was higher for SC data than PC though only when the exposure severity was considered. They concluded that perhaps the potential of SC Doppler had been underestimated,[3] although on reflection, this must be tempered by the higher severity of the dive profile used to reach this finding.

Since then, products such as the O'Dive™, which draws on the simplicity of SC Doppler monitoring have entered the market. They allow divers to perform their own measurements in the field without training to try and determine their own DCS risk using a novel severity index, and this has brought the validity and usefulness of SC measurements into question. Bubble monitoring can also be carried out using echocardiography, which is becoming more popular in research versus Doppler, as this technique is easier to learn with visible bubbles very apparent.[2] In one study it has been reported that SC Doppler measurements can correlate highly with echocardiography measurements in the heart.[4] However, this is contentious, with some suggestion that the correlation might have been due to the use of an extreme dive profile that caused a high incidence of high bubble grades (mean depth of 97.3 msw) and a small sample size (n = 6) so not dissimilar to the drawback of the Hugon study.[3–5] In contrast, another study has shown that SC grades had only fair to poor agreement with 2D echocardiography, with the SC site yielding lower bubble grades generally,[6] and this was corroborated in a study by Karimpour et al.[5] If SC measurements often underreport bubble load, then their use as an indicator of DCS risk should be treated with caution. Overall, it seems that the value of SC Doppler monitoring is equivocal and bears further investigation.

With renewed interest in travelling to the moon, establishing a lunar base, and performing further research and exploration (NASA Artemis program), remote Doppler monitoring for astronauts might be of benefit to assess DCS risk. NASA has recognised that such technology would be useful in understanding the risk of DCS in extra-vehicular activities for many years, although an operational system was not realised despite relatively successful research and development.[7] With improvements in technology, including new spacesuit designs, monitoring equipment, and the possibility of automated bubble grading systems for quick and consistent VGE assessment,[8] in-suit Doppler monitoring might now be a possibility, so determination of the most optimal monitoring position/s might be of benefit. Echocardiography is another often used measured of quantifying bubble loads but is too complex and bulky for under-suit deployment.

As part of a funded Office of Naval Research project initiated in 2020, the University of California at San Diego (UCSD) along with other partners including the University of North Carolina at Chapel Hill, the Divers Alert Network, Duke University (all US), and QinetiQ, UK, are currently curating a large database of Doppler audio recordings and metadata acquired previously, which at present holds around 6,700 individual Doppler recordings. This UCSD database represents a vast undertaking in terms of locating data, obtaining permissions for inclusion, digitising, cutting, and pairing recordings to their metadata, with the end goal to make these historic and valuable Doppler recordings available to the diving community. Most of these data include PC and SC rest and movement measurements for each diver as recommended at that time, so an opportunity to compare the Doppler grades from each site became apparent. The aim of this study was to make a retrospective comparison of PC and SC bubble grades in this large collection of data to determine the level of agreement between Doppler signals measured at both sites.

Methods

This study was determined exempt from Institutional Review Board requirements under US Federal Policy for the Protection of Human Subjects ("Common Rule") 45CFR 46.104(d) (4) by the University of California at San Diego (UCSD) Institutional Review Board (IRB) (determination #805229).

Data were drawn from Doppler recordings included in the UCSD database and originally made during the Mark 15 and Mark 16 air algorithm decompression trials carried out at the Naval Experimental Diving Unit (NEDU) of the US Navy in the 1980s. All subjects were male of age range 17–44 years. These dives were performed to a range of depths from 59 ft (18 m) to 300 ft (91 m), with total dive times varying from six minutes to 90 minutes. All were made using either heliox gas (helium and oxygen) or an oxygen/nitrogen mix, with a constant oxygen partial pressure of 71 kPa (0.7 atmospheres absolute [atm abs]). Doppler grading was carried out by experienced NEDU staff, and a selection of the grades were assessed and corroborated on their inclusion to the database for quality control by one of the authors (SLB) who has over 20 years of experience of grading Doppler bubbles. A note of any cases of DCS in the data included in this analysis was also reported.

DOPPLER GRADING

All Doppler measurements were graded using the Kisman Masurel (KM) Doppler grading system,[9] which was developed in 1984 to succeed the more basic Spencer scale[10] with the idea that the greater detail afforded would provide a system that could be used by a computer program. It also provides larger scope for classification of the bubble signals and allows measurements to be made following movement, which is often used to 'flush bubbles out' if they cannot be heard at rest.[1]

The KM system is made up of a three-part code representing the frequency, percentage/duration, and amplitude of any bubbles that are audible to the Doppler grader. This code is then translated into a KM grade between 0–IV. The system is subjective to the individual grader, though training helps to standardise measurements. The scale is non-linear; a grade of KM I may be derived if a listener hears only one bubble pass through a vessel over 10 heartbeats, and so essentially the diver can be thought of as nearly bubble free and close to KM 0. However, a KM II represents 3–8 bubbles, a KM III 9–40 bubbles, and KM IV a continuous stream of bubbles. Therefore, the low KM grades (0–I) can be said to be much closer to each other in terms of numbers of detected bubbles. The ordinal nature of the grading scale means that any statistical analysis should be made using non-parametric tools.

COMPOSITION OF MEASUREMENT SETS

Following each dive, Doppler measurements were made at the PC and SC sites (Figure 1) as per the following protocol:

- One precordial (PC) measurement at rest, followed by three movement measurements (deep knee bend) ($n = 4$)
- One resting measurement at the left subclavian (SC) vein site, followed by three movement measurements ($n = 4$) (squeezing hand into a fist)
- As for the left SC, one resting measurement at the right subclavian vein, followed by three movement measurements ($n = 4$)

Therefore, the total number of measurements for each site were PC $n = 4$ and SC $n = 8$, so for each diver at each time point this protocol provided 12 Doppler measurements.

ANALYSIS OF SETS

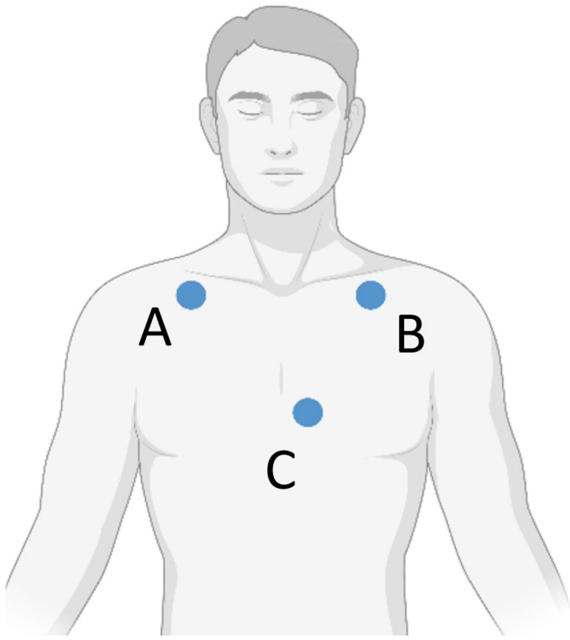
For the present retrospective analysis, all records held in the database that had complete sets of 12 measurements were included. Each set was assessed to see:

- If the resting PC KM grade matched the highest resting SC KM grade
- If the highest movement PC KM grade matched the highest movement SC KM grade
- If not matching, was the SC KM grade higher or lower than the PC grade
- If the right SC grade matched the left SC grade

In addition, we determined the number of sets where:

- Both PC and SC matched
- There were matching measurements of KM 0
- The SC and PC grades did not match but were close

Figure 1
Doppler monitoring sites; A – right subclavian; B – left subclavian; C – precordial



With regards to match analysis, as there were two resting SC grades (left and right) corresponding to one PC grade, and six movement SC grades corresponding three PC grades, the highest overall SC grade was compared to PC. Thus, a PC resting grade of KM I was said to match when compared with two SC resting grades made up of KM 0 and KM I grades, with the KM grade I counting in this case; conversely a PC resting grade of 0 was said not to match with SC grades KM 0 and KM I, as the highest SC grade recorded was KM I.

With respect to the final assessment point above, in many cases where low KM grades (KM 0 and I) had been recorded, the 'overall picture' of the bubble load between PC and SC grades may have looked very similar despite not being a definitive match (see the KM 0 and I examples above) and these were worthy of note.

Table 1
Kappa statistic interpretation (adapted from Landis et. al 1977)[11]

Kappa coefficient	Interpretation
Below 0.00	Poor
0.00–0.20	Slight
0.21–0.40	Fair
0.41–0.60	Moderate
0.61–0.80	Substantial
0.81–1.00	Almost perfect

Table 2
Assessment of precordial (PC) and subclavian (SC) agreement; KM – Kisman Masurel; *Percentages are derived from the total unmatched, not the total number of sets. KM, Kisman Masurel; PC, precordial; SC, subclavian

A – Total number of data sets, *n* = 453	Matched *n* (%)	Unmatched *n* (%)
Resting	281 (62)	172 (38)
After movement	176 (39)	277 (61)
Zero grades (PC and SC)	144 (32)	–
Sets where both PC and SC matched	155 (34)	–

B – Total number of data sets, *n* = 453	Unmatched* *n* (%)
Resting SC higher (%)	121 (70)
Resting SC lower (%)	51 (30)
After movement SC higher (%)	127 (46)
After movement SC lower (%)	150 (54)
Overall grades rest and movement KM 0 or 1 (%)	56 (12)

STATISTICS

The PC and SC sets were compared using weighted kappa statistics with quadratic weights, which deal with ordinal data more effectively than Cohen's kappa statistic for which the agreement is binary.[5] The weighted treatment deals better with the greater disagreement between a KM I and KM IV than the smaller disagreement of a KM 0 and I for example, which occurs when using this non-linear scale as described in the previous section. A proposed interpretation of the kappa statistic is provided in Table 1.[11] Descriptive statistics were also used to illustrate the distributions where appropriate.

Results

Precordial and SC Doppler (rest and movement) measurements were compared, drawing data from the UCSD database. At the time of the analysis, the database contained 6,735 Doppler recordings/metadata. Of these, 453 complete sets of 12 measurements were available (5,436 Doppler recording clips) from 129 subjects (Table 2).

There were ten individual DCS cases, nine with Type I DCS (eight pain only, one pain and mild sensory symptoms), and one Type II case (sensory) (Table 3). The DCS incidence in the sample population (n = 129) was 7%. Kisman Masurel grades associated with the DCS cases ranged from KM 0 at both sites to the highest grade, KM IV. The distribution of cases across the grades was fairly even (Table 4).

There were 281 (62.0%) matching PC and SC grades at rest (weighted kappa agreement 0.33, 95% CI ± 0.04), and only 176 (38.9%) matching PC and SC grades following movement (0.29 ± 0.02) (Tables 2, 5 and 6, and

Table 3
Decompression sickness (DCS) cases and Kisman Masurel (KM) bubble grades at each site; PC – precordial; SC – subclavian

DCS case	DCS type	Symptom	Max PC KM grade	Max SC KM grade
1	Type I	Pain	**II**	0
2	Type I	Pain	I	**III**
3	Type II	Sensory	I	II
4	Type I	Pain	0	**IV**
5	Type I	Pain	0	**I**
6	Type I	Pain	0	0
7	Type I	Pain	**IV**	III
8	Type I	Pain	0	**III**
9	Type I	Pain	**II**	I
10	Type I	Pain and sensory	0	**I**

Table 4
Distribution of decompression sickness (DCS) cases across Kisman Masurel (KM) grades and sites; PC – precordial; SC – subclavian

Maximum KM Grade	DCS cases	Site
0	1	–
I	2	2 SC
II	3	2 PC, 1 SC
III	2	2 SC
IV	2	1 PC, 1 SC

Table 5
Contingency table for precordial (PC) vs subclavian (SC) at rest; the weighted kappa of agreement was calculated as 0.33 ± 0.04. KM – Kisman Masurel

Monitored site/grade		SC grade					Totals
		KM 0	KM I	KM II	KM III	KM IV	
PC grade	KM 0	259	61	20	21	0	361
	KM I	16	8	4	7	1	36
	KM II	8	4	5	5	1	23
	KM III	14	2	7	8	1	32
	KM IV	0	0	0	0	1	1
Totals		297	75	36	41	4	**453**

Table 6
Contingency table for precordial (PC) vs subclavian (SC) after movement; the weighted kappa was calculated as 0.29 ± 0.02. KM – Kisman Masurel

Monitored site/grade		SC grade					Totals
		KM 0	KM I	KM II	KM III	KM IV	
PC grade	KM 0	133	90	19	12	1	255
	KM I	19	21	9	7	1	57
	KM II	23	19	12	7	1	62
	KM III	18	24	12	9	3	66
	KM IV	2	3	4	3	1	13
Totals		195	157	56	38	7	**453**

Figure 2
Bland-Altman plot for precordial (PC) vs subclavian (SC) at rest; showing a small bias (SC overestimating PC by 0.23 grades on average) and 95% confidence intervals of -2.39 to 1.93 Spencer grades

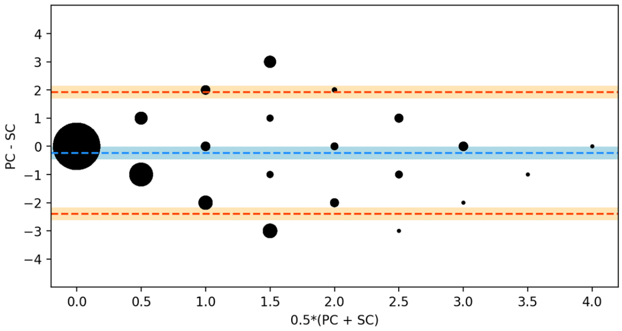


Figure 3
Bland-Altman plot for precordial (PC) vs subclavian (SC) after movement showing negligible bias (0.044 Spencer grades in favour of PC) and 95% limits of agreement from -2.6 to 2.69 Spencer grades

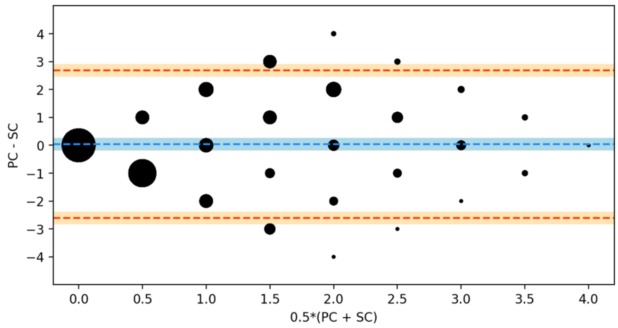


Table 7
Contingency table for right subclavian (SC) vs left SC at rest; KM – Kisman Masurel

Monitored site/grade		Left SC grade					Totals
		KM 0	KM I	KM II	KM III	KM IV	
Right SC grade	KM 0	297	31	12	7	0	347
	KM I	36	8	1	0	0	45
	KM II	14	7	2	4	0	27
	KM III	19	3	3	5	0	30
	KM IV	0	0	2	1	1	4
Totals		366	49	20	17	1	**453**

Table 8
Contingency table for right subclavian (SC) vs left SC after movement; KM – Kisman Masurel

Monitored site/grade		Left SC grade					Totals
		KM 0	KM I	KM II	KM III	KM IV	
Right SC grade	KM 0	195	49	11	3	2	260
	KM I	77	31	8	1	0	117
	KM II	20	10	7	7	0	44
	KM III	7	12	4	4	0	27
	KM IV	0	1	0	2	2	5
Totals		299	103	30	17	4	**453**

Figures 2–3). One hundred and fifty-five data sets matched both at rest and after movement, and 144 of these were grade KM 0 with no bubbles detected in either site. There were 56 sets of data that did not match but had grades no higher than KM I.

Of the unmatched data (rest *n* = 172; movement *n* = 277), resting SC grades were higher than the corresponding PC grade in 121 (70.3%) data sets and lower in 51 (29.6%). After movement, SC grades were higher in 127 (45.8%) and lower in 150 (54.2%).

The degree of agreement between the left and right subclavian measurements was also assessed. At rest, the overall agreement was 69% between left and right SC (Table 7), and after movement this reduced to 53% (Table 8).

Discussion

This retrospective study used a large post-dive Doppler dataset to compare the KM grade agreement between measurements made in the PC and SC measurement positions, finding that there was a large discrepancy between the two. At rest, 62% of measurements matched, while after movement this correlation was reduced greatly to only 39%. The present agreement at rest is considerably higher than that found in one study comparing SC Doppler (using the O'Dive™ device) to PC echocardiography, which found perfect agreement in only 34% (n = 1,113) of its measurements, however both studies note a considerable discrepancy between the two sites.[6] The weighted kappa coefficients indicated fair agreement between PC and SC (0.33 at rest and 0.29 after movement) indicating overall reasonable agreement. This divide between PC and SC measurements represents a challenge for diving research given there is general agreement that the highest bubble loads align with the greatest risk of DCS, and in the field workers rely generally on one site or the other from which to measure their data.[1,12,13] With this level of disagreement, which site is the most beneficial?

It should be said that historically, it was noted that the optimal way to gain the best prediction of DCS occurrence was to combine the maximum bubble grades from both sites (SC and PC) as per Nishi et al, where the relatively large number of DCS cases (69 cases: 35 after air dives, 34 after heliox dives) gave further clarity to this approach.[1] Following the air dives, DCS occurred when there were no observable bubbles in the precordial region, however, bubbles were found in the SC veins.[1] Thus, in this large set of air dive data (1,726 subjects) the occurrence of DCS was always accompanied by bubbles, so it was suggested for completeness both sites should be monitored.[1] One case of DCS was noted without the presence of bubbles but this was following heliox dives.[1] Their data also showed that the incidence of DCS increased with higher KM grades III and IV; of the 69 cases, 38 (55%) were accompanied by a KM III, and 24 (35%) a KM IV.[1]

In the present study, there were 10 cases (10 subjects) of DCS noted and interestingly, the associated maximum KM grades varied considerably (Table 3) ranging from KM 0 to KM IV at both sites, with a reasonably even distribution of cases across the KM grade range (Table 4). This pattern is not reflective of the Nishi results, but our findings should be tempered by noting there were only 10 DCS cases observed in the present data, which may be too small to reflect trends accurately. However, on calculation of DCS incidence within the sample population, this value was found to be higher (7.8% [n = 129]) than the Nishi study (2.0% [n = 1,726] for air dives, and 1.9% [n = 1,773] for heliox dives respectively), which confounds the small sample size argument somewhat.[1] Another point to note is that in the one DCS case where no bubbles were observed in the present study, the breathing gas was air, not heliox as in the Nishi data. That DCS was observed in the absence of detected bubbles is very unusual, with a general agreement that the condition does not occur without the presence of venous gas emboli post-dive. However, in this dataset, only two measurements were made after the exposure, at 34 and 300 minutes after return to surface. Thus, we should be careful and not say that bubbles were not present, but rather bubbles were not detected in this individual at these two timepoints, as in fact they could have evolved at other points post-dive. It is for this reason that the 2016 consensus recommended that measurements should be made within 15 min following decompression and at intervals no greater than 20 mins for the first 2 h post-dive.[2] Indeed, the more measurements made then the better we are able to say with any confidence that bubbles are present or not.[14]

Despite the slight disparities between the present study and the Nishi data, and the further limitation that we do not have access to all metadata for the individual dives in our dataset, given the larger size of the Nishi dataset perhaps the more conservative approach to bubble monitoring would be to measure at both sites. However, this is not always practicable, particularly in the field as it requires different Doppler equipment (probes of different frequencies) and much longer monitoring sessions, making the technique slightly limiting.

If this technology is to be used effectively in the future, the option to monitor subjects remotely and even grade the Doppler signals in real-time is an attractive prospect. As mentioned previously, NASA is currently renewing its interest in lunar exploration and DCS does pose a problem in the space environment. A real-time, remote monitoring system would be of great benefit in this setting. Current work across many research and development centres is proceeding to streamline and reduce the size of essential physiological life-support monitoring sensors to measure parameters such as heart rate, hypoxia, pulmonary barotrauma/arterial gas embolism, hypercapnia, and hyperoxia, in order to allow in-suit use. It would not be ideal to have to attach three relatively large Doppler probes to the torso as body space is at a premium, therefore a reductive approach to bubble monitoring is of prime importance. If a single site was confirmed as providing an acceptable estimation of DCS risk, all the better. On consideration of the data assessed in the present study it was noted that of the unmatched resting measurements, maximal SC grades were higher than PC grades in 70% of cases, while following movement, maximal SC grades were higher in only 46%; this equivocal finding is as expected given the results shown in the Bland Altman plots depicted in Figures 2 and 3. In the Plogmark study comparing Doppler SC to PC echocardiography, only 8% of SC measurements were higher than PC values, representing an even greater skew towards the capacity of the PC site to report the higher grades.[6] Importantly in our study, the large 95% limits of agreement between PC and SC and negligible bias suggest that one site cannot be favoured over another.

Of course, bubble grades could vary at the PC and SC sites for reasons other than those already mentioned. For example, a measurement is only a snapshot of a moment in time;

dependent on the dive profile used, post-dive bubbles may be constantly evolving and moving back to the heart in the venous circulation, or only develop at certain time points that means they can be missed, as noted earlier in the discussion.[13] Graders making audio Doppler measurements generally listen to at least 10 heartbeats for each measurement and often more, particularly if bubble sounds are rare and it is suspected that no bubbles are present. Precordial measurements including rest and movement could take two to three minutes to complete, with the grader then moving on to monitor the SC site. With these delays between measurements, bubbles could evolve or disappear in that time and so cause discrepancies. In the Plogmark study, timing of measurements was considered in 850 paired grades that had no more than five minutes between PC and SC grading. Although this could also be said to be too long a delay, analysis of these timed data found the same poor level of agreement.[6]

An additional confounder to PC versus SC is that the PC site is notoriously more difficult to monitor, often due to cardiac noise artefacts and to differences in anatomy between subjects, with deep chested individuals being notoriously difficult to optimise probe placement, so monitoring can be less accurate. However, despite these limitations the data considered in the present study although equivocal in terms of PC or SC reporting maximal grades more frequently, was of good quality.

Conclusions

The 2016 consensus on ultrasound monitoring for diving research advised that the PC site should be used as standard for Doppler monitoring given that it reports whole body venous return and that SC measurements could be useful to provide additional information. The current collection of Doppler data that form the UCSD database has allowed a retrospective investigation to verify or disprove this recommendation. Overall, our findings regarding maximal bubble grades suggest that differences between the two are equivocal, and dependent on many factors including resting/movement, timing of measurements etc. If remote monitoring of bubbles proceeds in the future, we suggest that if a site must be preferred, it be the PC position, given bubbles from the whole body can be examined from this site, while noting that SC measurements cannot be discarded as they provide additional information. A definitive study conducting a head-to-head assessment of different monitoring sites after separate limb movements with recent devices is perhaps necessary for a definitive finding.

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