

Ultrasound protocols used to detect vascular gas emboli in divers: a systematic review

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Keywords

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Abstract

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Introduction: Venous gas emboli (VGE) detected via ultrasound can be used as a surrogate marker for decompression stress. While Doppler ultrasound is the historical gold standard, two-dimensional (2D) ultrasonography offers advantages for on-site monitoring, including a wider field of view and reduced dependence on noise-free environments. This systematic review evaluates 2D ultrasonography protocols used in decompression research since the 2015 International Meeting on Ultrasound for Diving Research, identifying methodological similarities, differences, and adherence to consensus recommendations.

Methods: A search of PubMed and Scopus identified studies using 2D ultrasound to detect VGE in divers. Inclusion criteria were: (1) use of 2D ultrasound, (2) detection of VGE or monitoring of decompression stress, (3) inclusion of a diver cohort, and (4) publication after 2015. Data extraction focused on VGE scoring systems, ultrasound hardware, measurement protocols, and operator experience. Risk of bias was assessed using ROBINS-I-V2, and compliance with the 2015 consensus recommendations was evaluated.

Results: Twenty studies were included. The Eftedal-Brubakk scale was most commonly used ($n = 15$), with cardiac ultrasound as the primary imaging modality; one study assessed a peripheral vessel. Common shortcomings included post-dive measurements lasting less than two hours, underreporting of operator experience and hardware specifications, limited individual-level data, and inappropriate use of parametric statistics for ordinal bubble grade data. No study fully complied with all consensus recommendations.

Conclusions: This review demonstrates that, although two-dimensional ultrasound is widely used for post-dive VGE assessment, methodological heterogeneity with multiple shortcomings remain. Furthermore, nearly all studies restricted imaging to the heart, thus leaving peripheral vessel assessment largely unexplored.

Introduction

Humans entering aquatic environments undergo physiological changes. Aside from the specific cardiovascular and pulmonary adaptations, profound changes occur when a self-contained underwater breathing apparatus (scuba) is used. Descending under the water surface during scuba diving exposes the body to progressively higher ambient pressure as depth increases, causing inert gases to dissolve and accumulate within tissues. The speed of this accumulation depends not only on tissue perfusion and gas solubility but also on the surrounding pressure. When ascending, the

ambient pressure is reduced. If the pressure of dissolved gas in tissue exceeds ambient pressure the gas may nucleate into bubbles.¹ Risk factors for bubble formation include longer and deeper dives (with more gas accumulation) and rapid ascents.¹

Decompression sickness (DCS) may occur when these bubbles form in tissues or blood, causing ischaemic, inflammatory, or mechanical injury. DCS is highly variable in nature and severity and can affect multiple organs including the brain, spinal cord, inner ear, musculoskeletal system, cardiopulmonary system, and skin.¹ The quantity

of venous gas emboli in the bloodstream can be used as a surrogate marker for the amount of decompression stress experienced by the diver.²

Doppler ultrasound is historically considered the preferred method for quantifying inert gas bubbles in the venous blood, referred to as venous gas emboli (VGE). Doppler has been used to validate novel decompression tables.³ Two-dimensional (2D) ultrasonography is a viable alternative tool for decompression stress monitoring. One advantage is that it allows for a more extensive field of view of the structure of interest.³ Other advantages of two-dimensional ultrasound imaging include its potential for training a wide range of personnel and reduced dependence on a noise-free environment compared to Doppler analysis, enhancing its suitability for on-site monitoring.³

A 2011 review highlighted the lack of standardised ultrasound protocols for assessing decompression stress, limiting cross-study comparability.⁴ In 2015, The International Meeting on Ultrasound for Diving Research was held. During this meeting, experts discussed the strengths and limitations of ultrasound monitoring and presented numerous recommendations for a standardised protocol including recommendations for measurement timing, provocative movements and data analysis.⁵

This systematic review aims to offer an overview of the 2D ultrasonography protocols used in decompression research published in peer reviewed journals and performed after 2015 consensus meeting. Methodological similarities and differences were assessed, and recommendations are provided for future studies.

Methods

This systematic review was conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guideline.⁶ On 16 September 2025, we searched PubMed and Scopus for studies using ultrasonography to detect VGE in divers. The search strategy combined three items: (1) ‘diving’, (2) ‘decompression sickness’, or ‘decompression stress’ and related terms and (3) ‘ultrasound’ and related terms using Boolean operators such as “or”, and “and”. The full search strings are depicted in Table 1. Only English-language articles published after 2015 were included.

INCLUSION AND EXCLUSION CRITERIA

Articles were initially screened by title and abstract, followed by a review of the full text. Inclusion criteria were: (1) use of a two-dimensional (2D) ultrasound diagnostic technique, (2) detection of venous gas emboli or monitoring of decompression stress, (3) inclusion of a cohort of divers and (4) publication after the publication of the recommendations of 2015 consensus meeting. Exclusion criteria were: (1) no description of measurement protocol provided, (2) not an original research article (e.g., a case report or a meta-analysis) and (3) no full text available. Case reports were excluded because this study focuses on evaluating the methodologies used in original research using ultrasound to assess VGE.

DATA COLLECTION

Data extraction was performed separately by two authors (BT and TW) using a standardised spreadsheet. Discrepancies

Table 1
Search query

PubMed:
("diving"[MeSH Terms] OR "diving"[All Fields] OR "Scuba"[All Fields] OR "Submersion"[All Fields])
AND
("decompression sickness"[MeSH Terms] OR "decompression"[All Fields] OR "gas embol*" [All Fields] OR "bubble*" [All Fields] OR "Venous Gas"[All Fields])
AND
("ultrasound"[Title/Abstract] OR "echo"[Title/Abstract] OR "echocardiography"[All Fields])
Scopus:
("diving" OR "scuba" OR "submersion")
AND
("decompression sickness" OR "decompression" OR "gas embol*" OR "bubble*" OR "venous gas")
AND
("ultrasound" OR "echo" OR "echocardiography")

Table 2Summary of consensus recommendations following The International Meeting on Ultrasound for Diving Research in 2015⁵

#1	Clearly describe ultrasound operator training/experience, or ensure blinded independent review.
#2	Use the original or an expanded Eftedal-Brubakk scale for 2D imaging.
#3	Employ repeated-measures designs with participants as their own controls.
#4	Use the apical window as the standard for two-dimensional imaging.
#5	Standardise and report diver position during monitoring.
#6	Always include resting measurements with a standardized rest period; if provocation is used, describe and report both rest and provocation results.
#7	Record for at least 120 minutes post-decompression, or longer if bubbles persist.
#8	Make the first measurement ≤ 15 minutes post-dive; intervals ≤ 20 minutes during the first 120 minutes.
#9	Provide unpooled data when possible to enable reanalysis.
#10	Report individual-level outcomes regarding bubble grades (onset, maximum grade, time to max, medians, ranges, modes, zero grades) and raw data if feasible.
#11	Use non-parametric methods for bubble grade data.
#12	Acknowledge the limitations of bubble data.
#13	Record and preserve data for future review.
#14	Carefully consider comparability of different devices and methods; describe both in detail.

were discussed until consensus was reached. Extracted variables included: the VGE scoring system, ultrasound hardware description, number of dives and divers in the study, and study objectives, measurement locations and techniques, use of provocative movements and measurements at rest, time intervals between measurements, diver positioning, and description of the experience of the ultrasound performer.

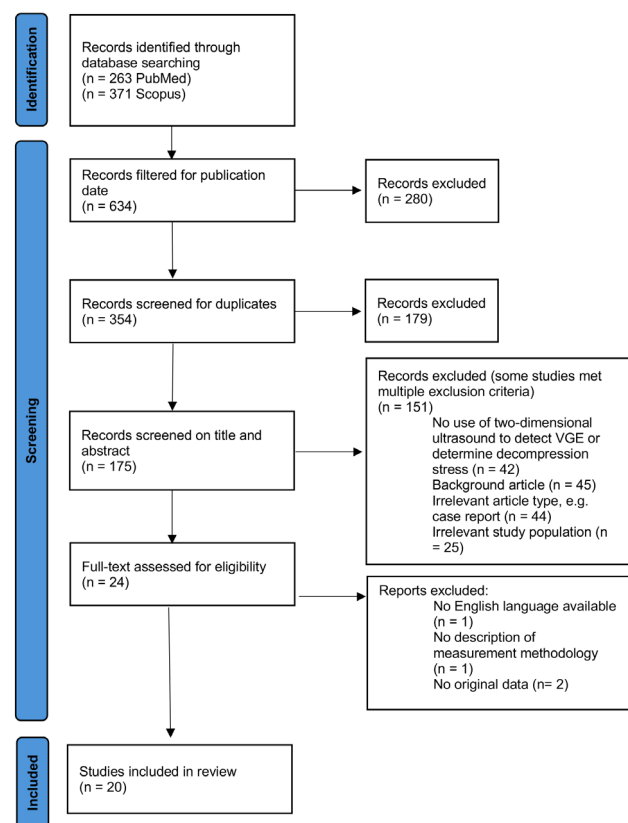
QUALITY ASSESSMENT

Risk of bias in individual studies was assessed independently by BT and TW using the standardised ROBINS-I-V2 tool,⁷ an updated version of ROBINS-I.⁸ Discrepancies were resolved by discussion until consensus was reached.

Further quality assessment was performed by evaluating the studies against the recommendations of the 2015 consensus,⁵ summarised in Table 2. For each recommendation a study was scored either 'Yes' if it complied with the recommendation, 'No' if it did not, and 'Partial' if it did not fully comply. For example, 'Partial' was assigned if the ultrasound technique was described as "cardiac" without specifying the apical view. Criterion 9 was scored 'Yes' if bubble score categories were reported separately; criterion 10 if individual bubble scores were presented; and criterion 11 'Partial' if both parametric and non-parametric analyses were used. Criterion 13 was not assessable. Criterion 14 was scored as 'Yes' if the study contained a clear description of utilised ultrasound hardware.

Results

The search yielded 263 PubMed and 371 Scopus records. After screening for publications before the International Meeting on Ultrasound for Diving Research 354 articles remained. Of these, 179 were duplicates and were excluded. Of the remaining unique 175 articles, 151 articles were

Figure 1
PRISMA flowchart

excluded based on title and abstract. Of the remaining 24 articles, one did not provide a description of ultrasound methodology used and used an existing database⁹ and one was excluded due to unavailability of the English full text.¹⁰ Two were excluded due to the absence of original data.^{11,12} The 20 remaining articles were included (Figure 1).

STUDY CHARACTERISTICS AND RISK OF BIAS

A summary of the extracted data is provided in Table 3. Study populations ranged from small, controlled cohorts of 10–20 dives^{13–16} to larger multi-dive studies.^{11,12,17,18} Study goals were equally diverse (Table 4), including the comparison of inter-diver bubble formation and agreement between handheld Doppler and cardiac ultrasound.

Among the studies, using the criteria of the ROBINS-I-V2 tool results in one study with a serious risk of bias and 19 with a moderate risk of bias. A complete overview of the risk of bias is depicted in Table 3. *[Appendix A](#) provides details on the scoring method.

SYNTHESIS OF METHODOLOGIES

Most studies used the Eftedal-Brubakk (EB) scale or its modifications for quantifying VGE;^{15,17–25} others used VGE counting.^{26–29} Two studies combined multiple scoring systems, using both VGE counting and the (modified) EB scale.²⁶ Two studies exclusively used VGE counting.^{30,31}

Ultrasound hardware ranged from high-end scanners such as the General Electric (GE) Vivid-Q (GE Healthcare, Chicago, IL, USA)^{16,20,22} and GE Logic E (GE Healthcare, Chicago, IL, USA),¹⁷ to portable systems, including the Vivid-I (GE Healthcare, Chicago, IL, USA)²⁷ and Butterfly iQ.²⁵ Three studies did not specify the hardware used.^{11,14,19,32} Probe frequencies and types were inconsistently reported.

Studies used different descriptions for the cardiac views they obtained. However, the descriptions of the majority of the studies corresponded to what is usually called the apical four-chamber view,^{11–13,15,16,18,20,21,23–26,28,30–32} Two studies described extending the view to apical or multi-chamber views including the heart base, inferior vena cava, and subcostal regions.^{16,23} The common theme in these positions was that all studies except one exclusively imaged the heart and did not assess (peripheral) vessels.

Half the studies measured VGE only at resting conditions.^{12,15,17–19,23–27,29} Others also after limb flexion or extension,^{11,16,20,21,28,30–32} after a Valsalva manoeuvre¹⁴ or after two coughs.²² One study had divers perform an exercise on an ergometer specifically tailored to their study goal and took ultrasound measurements prior to, during and after this exercise.¹³

Post-dive measurement timing varied. Five studies measured only once.^{14,17,22–24} The fastest measurement performed was repeated as ‘immediately’ post-dive¹⁵ and the latest was at 126 minutes post-dive.²⁹ Most studies followed specific time-intervals, while two performed scans if bubbles were present.^{15,25}

Divers were most commonly positioned left lateral decubitus (or recumbent or supine lateral) position.^{11,12,14,15,18–21,25,31,32} Six used the supine position.^{13,16,17,22–24} Five studies did not specify the diver’s positioning.^{26–30}

Operator experience was rarely reported.^{11,15–17,20,23,25,27–32} Some studies describe their operators as trained or certified sonographers,^{13,14,24} experienced operator,¹⁹ experienced cardiologists,²² physicians^{18,21} or experienced researcher.²⁶

COMPARISON TO RECOMMENDATIONS

Compliance with the 2015 consensus recommendations is shown in Table 5. No study met all of the 14 outlined criteria; Hjell et al. complied with the largest number ($n = 11$).²¹ It should be noted that the items included in the consensus guideline do not contribute equally to data quality. In particular, recommendations related to data collection are crucial for data quality. All studies acknowledged the limitations of using bubble data for analysis. All but one study included resting measurements and, if applicable, described the performed provocation method. Use of the EB scale or modified EB scale was common ($n = 15$), and repeated measures designs with participants serving as their own controls were implemented in 12 studies. The apical window was used as the standard for two-dimensional imaging in 18 studies, and diver positions were standardised and reported in 17 studies. Non-pooled bubble grading data were reported in 15 studies, and non-parametric statistical methods were appropriately applied in 12 publications. Notably, studies using VGE counting do not necessarily need to use non-parametric analyses.

As stated before, no study clearly reported the training or experience of the ultrasound operator. Other recommendations that few studies met include prolonged post-dive recording of at least 120 minutes ($n = 6$), reporting of individual-level bubble outcomes ($n = 2$), and performing the first measurement within 15 minutes post-dive and utilising intervals of 20 minutes or shorter during the first 120 minutes ($n = 2$).

Discussion

To our knowledge, this study represents the first systematic review of research using 2D ultrasound to assess VGE in divers since the 2015 consensus. Twenty studies met the inclusion criteria, encompassing a broad range of study sizes and objectives.

KEY FINDINGS

The key findings of this study are: (1) No study complied with all 14 recommendations of the 2015 consensus. (2) All but one study exclusively obtained cardiac imaging.

*Footnote: Appendix A is available online on our website: <https://www.dhmjournal.com/index.php/journals?id=438>

Table 3

Characteristics of included studies ordered by publication date; DCJEM – Defence and Civil Institute of Environmental Medicine; DCS – decompression sickness; EB – Eftedal-Brubakk; GE – General Electric; Ref – reference number; TTE – transthoracic echocardiography, VGE – venous gas emboli

Year	Ref	Scoring system	Ultrasound hardware	Included study population	Locations	Movement	Time intervals	Position of diver	Ultrasound operator	Risk of bias
2015	15	EB	Zonare Z1	24 dives, 24 divers	Right ventricular foreshortened apical view	No	Immediately post-dive, every 15 minutes until 75 minutes or two clear scans	Supine left lateral	Not specified	Moderate
	13	Modified EB	Vivid Q, and contrast TTE (unspecified)	20 dives, 20 divers	Apical four-chamber, temporal window median cerebral artery and unspecified for TTE	Yes, prior to and during supine ergometer exercise until exhaustion	15, 30 and 45 minutes post-dive. Then every 2 minutes during exercise and after 10 minutes of recovery	Supine	Trained ultrasonographer	Moderate
2016	14	Modified EB and VGE counting	Not specified	11 dives, 11 divers	Apical four-chamber	Valsalva maneuver	60 minutes post-dive	Recumbent position	Certified sonographer	Moderate
	16	Modified EB scale	GE Vivid-Q	16 dives, 16 divers	Apical four-chamber view	Yes, at rest and after arm and leg contractions	30, 60 and 90 minutes post-dive	Supine	Not specified	Moderate
	31	VGE counting	Vivid 7	36 dives, 6 divers	Modified four-chamber view	Yes, at rest and after two knee bends with flexion	Before dive and 30 and 90 minutes post-dive	Left lateral supine position	Not specified	Moderate
2017	19	EB	Not specified	38 dives, 10 divers	Precordial	Yes, at rest and some after flexing both legs while supine or knee bends when standing upright	5, 10, 15, 20, 25, 30, 45, 60, 75, 90, 105, 120 minutes post-dive	Left lateral decubitus position	One experienced operator	Moderate
	27	VGE count	Vivid-i	Between 36 and 54 dives, 9 divers	Transthoracic echocardiography	No	30, 90 minutes post-dive	Not specified	Not specified	Moderate
	23	EB	Not specified	74 dives, 51 divers	Apical four-chamber, heart base short-axis, inferior vena cava and right atrium subcostal	No	30 minutes post-dive	Supine	Not specified	Moderate

Table 3 continued.

2018	29	VGE counting	Mindray M9	17 dives, 14 divers	Modified four-chamber view B-mode echocardiography recording	No	21, 56, 91, 126 minutes post-dive	Not specified	Not specified	Moderate
2019	22	Modified EB	Vivid Q	30 dives, 10 divers	Cardiac	At rest and after two coughs	Before dive and 30 minutes post-dive	Supine	Two experienced cardiologists	Moderate
2020	32	Modified EB	Not specified	96 dives	Apical long-axis four-chamber view	Yes, at rest and after flexion of elbow and knee	20, 40, 60, 80, 100, 120 minutes post-dive	Left decubital position	Not specified	Moderate
2021	24	EB	GE Logic e	342 dives, 41 divers	Subcostal and apical	No	40 minutes post-dive.	Supine position	Not specified	Moderate
	20	EB	GE Vivid-Q	30 dives, 10 divers	Apical four-chamber view	Yes, at rest and after limb flexion.	Pre-dive once, 20, 40, 60, 80, 100, 120 minutes post-dive	Left lateral decubitus	One operator	Moderate
2022	18	EB	UltraSound EDGE II	152 dives, 48 divers	Apical four-chamber	No	Within 5–15 minutes, then every 15 minutes post-dive for 4–9 measurements	Left lateral decubitus	Two physicians	Moderate
	28	VGE count	Sonosite M-Turbo	16 dives, 8 divers	Apical four-chamber view	Yes, at rest and after two knee bends	30, 60 minutes post-dive	Not specified	Not specified	Moderate
	26	VGE counting and EB	Sonosite M-Turbo	30 dives, 10 divers	Four-chamber view	No	30, 60 minutes post-dive	Not specified	One experienced researcher	Moderate
	25	EB	Butterfly iQ and Vivid q	75 divers	Apical four-chamber view	No	Before and 20, 40, 60 minutes post-dive. Additional at 20-minute intervals if bubbles persisted	Lying on left side	Not specified	Moderate
2023	21	EB	EDGE II	154 dives, 47 divers	Apical four-chamber view	Yes, at rest and after knee extension while laying	Within 5–15 minutes, 30, 45, 60, 75, 90, 105, 120 minutes post-dive	Left lateral decubitus position	Two physicians	Moderate
2024	30	VGE counting	M9 Mindray and Sonosite M-Turbo	10 dives, 6–8 dives each	Apical four chamber view	Yes, at rest and after two knee bends	15, 30, 45, 60, 120 min post-dive.	Not specified	Two of the authors, experience not specified	Serious
2025	24	EB	GE Logic e	342 dives, 41 divers	Echocardiography using subcostal and apical approach	No	30 minutes post-dive	Lying supine position	Two experienced ultrasonographers with an international ultrasound diploma	Moderate

Table 4

The study goals of the included studies ordered by publication date; AGE – arterial gas embolism; DCS – decompression sickness; Ref – reference number; VGE – venous gas emboli

Year	Ref	Study goal
2015	15	Comparing bubble formation between divers with- and without history of DCS.
	13	Assessing post-dive AGE formation.
2016	14	Assessing the effect of in-water recompression on VGE.
	16	Assessing the impact of pre-dive exercise on microparticles, endothelial function and VGE throughout multiple dives.
	31	Comparing the effect on post-dive VGE of different preconditioning methods: oxygenation, whole-body vibration and vibration associated with oxygenation. Assessment of how multiple days of deep diving influence bubble production, oxidative and inflammatory markers.
2017	19	Observing DCS and VGE following standardised diving protocol.
	27	Assessing the effect of different preconditioning interventions on VGE formation.
	23	Comparing the effect on inflammatory responses of two decompression procedures.
2018	29	Assessing variability in VGE counting in a standardised diving profile.
2019	22	Assessment of oxygen enriched gases on bubble formation and endothelial function.
2020	32	Testing air decompression schedules.
2021	24	Finding a relationship between dive profile and individual parameters and the severity of post-dive bubbles.
	20	Assessing decompression stress following a single dive at altitude.
2022	18	Assessing the agreement between handheld self-positioning Doppler and cardiac ultrasonography.
	28	Assessing whether pre-dive exercise reduces VGE.
	26	Monitoring post-dive physiological status and VGE dynamics.
	25	Comparison of handheld ultrasound devices to standardised ultrasound device.
2023	21	Safety evaluation of new diving table.
2024	30	Assessment of how multiple days of deep diving influence bubble production, oxidative and inflammatory markers.
2025	24	Quantifying inter- and intra-diver gas bubble variability.

(3) Ultrasound operator experience, detailed hardware descriptions and individual diver data were consistently underreported. (4) There was considerable methodological variability in measurement timing and number of total measurements per individual. (5) Multiple studies utilised parametric analyses for ordinal bubble grade data.

COMPARISON OF STUDY METHODOLOGIES

The EB scale and its modifications were the most commonly used grading systems, and cardiac ultrasound was the primary imaging modality; only one study included additional measurements of the subclavian vein. These findings are consistent with the 2015 consensus recommendations.⁵ Even though the descriptions used by the authors differed, it is safe to assume that almost all used the apical four-chamber view, which is considered the preferred method for assessing VGE in the right heart.⁵ No study extensively assessed (peripheral) vessels.

Measurement timing varied widely. It is commonly agreed that VGE appear in different patterns and differ over time due to a multitude of factors, including varying dive profiles and possible variability in (patho-) physiological factors within the diver.¹² Therefore, multiple measurements should be made to gain an accurate indication of the peak bubble load, as a surrogate endpoint for decompression stress.^{3,33} The different timings used by the studies diminish their comparability. A reason for the limited number of

measurements performed in multiple studies may be logistical or practical constraints. The recommendation is to perform measurements within 15 minutes and up to 120 minutes post-dive, with ≤ 20 minutes intervals. However, these timings can be difficult to achieve in real life, as divers may have other obligations to fulfil, including safety measures. Furthermore, the time to peak VGE varies across diving profiles. Accordingly, study protocols should be designed to ensure that peak VGE is not missed and that temporal resolution is sufficient across the entire post-dive window relevant to the exposure.

The majority of studies conducted VGE measurements at rest, with a subset incorporating assessments following provocative manoeuvres. However, these manoeuvres were not standardised across studies, ranging from lower-limb exercises (e.g., air squats) to upper-limb flexion. It is plausible that such heterogeneity in movement protocols may influence both the anatomical sites of bubble dislodgment and the overall quantity of detectable VGE.

Not all studies clearly or consistently reported differences in bubble load before and after provocation. This limitation does not necessarily detract from the validity of their findings, as bubbles dislodged by provocative manoeuvres are still considered indicative of decompression stress, and the manoeuvres themselves do not increase physiological stress. Currently, there is no scientific consensus regarding the exact interpretation of post-movement VGE grading using the EB

Table 5

Compliance of included studies with the guidelines provided by the 2015 consensus;⁵ F – full compliance with the corresponding guideline item; P – partial compliance; n/a – indicates that compliance could not be assessed; empty cells indicate non-compliance

Study		Gawthrop et al. ¹⁵	Barak et al. ¹³	Dituri et al. ¹⁴	Madden et al. ¹⁶	Balestra et al. ³¹	Blogg et al. ¹⁹	Germonpré et al. ²⁷	Spisni et al. ²³	Papadopoulos et al. ²⁹	Šegrt Ribičić et al. ²²	Andrew et al. ³²	Fichtner et al. ²⁴	Hess et al. ²⁰	Plogmark et al. ¹⁸	Lambrechts et al. ²⁸	Balestra et al. ²⁶	Karimpour et al. ²⁵	Hjelte et al. ²¹	Balestra et al. ³⁰	Fichtner et al. ²⁴	Studies in agreement with guideline
#1			P	P			P				P									P	P	0
#2		F	F	F	F		F		F		F	F	F	F	F		F	F	F	F	F	15
#3							F	F		P	F		F	F	F	F	F	F	P	F	F	11
#4		F	F	P	F	F	P	P	F	F	P	F	F	F	F	F	F	F	F	F	F	16
#5		F	F	F	F	F	F		F		F	F	F	F	F			F	F	F	F	15
#6		F	F		F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	19
#7							F			F		F		F	P					F	F	6
#8		P	P		P		F								P					F		2
#9		F	F		F		F		F		F	F	F	F	F				F	F	F	13
#10			F											F						P		2
#11		F	F		F		F			F	F	F			F		P	F	F	F	F	11
#12		F	F	F	F	F	F	F		F	F	F	F	F	F	F	F	F	F	F	F	20
#13		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
#14		F	F		F	F		F		F	F		F	F	F	F	F	F	F	F	F	16
Items in agreement		8	9	3	8	5	9	4	6	6	8	8	8	10	9	5	6	8	11	6	9	

scale.¹¹ Establishing standardised criteria for this assessment is critical, as bubble loads can differ substantially between pre- and post-movement measurements.

Several additional methodological inconsistencies were noted in the analytic approaches. First, bubble data were not consistently presented in a non-pooled format. Moreover, only two studies reported individual-level bubble grading outcomes. Finally, the use of parametric statistical tests in the analysis of ordinal bubble grade scales was inappropriate, as non-parametric methods would have been more suitable.

The absence of detailed reporting on ultrasound operator experience further limits the interpretability of the included studies. Proficiency in cardiac ultrasound within the context of diving medicine is particularly important, as the real-time detection and quantification of intravascular bubbles requires specific practical experience and insufficient expertise could result in underestimation of the actual number of VGE.

Ultrasound hardware was not consistently reported across studies, and where described, a wide range of devices were employed. To date, no consensus or large-scale evaluation has been established regarding the comparability of different ultrasound systems for VGE assessment, and existing evidence suggests that levels of correlation may vary across ultrasound hardware.²⁵ It is reasonable to assume that high-end ultrasound platforms provide superior image quality; however, the adequacy of smaller, portable devices for accurately assessing decompression stress remains uncertain. This question is of particular operational relevance for the future application of two-dimensional ultrasound in austere environments.

STRENGTHS AND LIMITATIONS

To our knowledge, this study is the first to systematically evaluate compliance with the 2015 ultrasound consensus recommendations in published studies. This is valuable knowledge for both reviewing and updating the recommendations and for helping authors of future studies design and publish relevant data in this area of research.

Several limitations of this review should be acknowledged. First, heterogeneity in reporting of the ultrasound protocols and diving populations used limited our ability to compare the studies and draw overarching conclusions. For example, due to the underreporting of the experience of ultrasound performers, it is difficult to draw conclusions regarding the quality and applicability of the images obtained in all studies using different protocols. This does not necessarily mean that the work is flawed, but that it can be difficult for readers to assess the presented data. A potential approach for the future is for editorial boards and reviewers to ensure that submitted manuscripts adhere to the consensus statements, encouraging authors to provide the required information or to justify deviations.

Second, the included studies are predominantly observational and non-randomised in nature, conducted in controlled experimental settings. This reduces the generalisability of our findings to operational, resource-constrained diving contexts. While we acknowledge that many studies in our field have 'convenience inclusions' or 'opportunistic data collection', it would benefit if future studies clearly evaluate the 'noise' that in vivo experiments introduce and discuss this in their manuscripts when applicable. For example, imaging conducted in waterside or field environments may differ in quality from imaging performed under controlled laboratory conditions. Accordingly, if ultrasound imaging is intended for operational use, validation studies should be designed to closely replicate the environments in which the technology is ultimately expected to be applied.

Third, there has possibly been a component of publication bias, as studies showing low or no VGE may be underreported, which potentially limits our understanding of ultrasound methodologies employed for decompression stress assessment. Furthermore, most of the included studies were assessed as having a moderate risk of bias using the ROBINS-I-V2 instrument, which means that the strength of conclusions should therefore be carefully considered. While this instrument is designed for assessing interventional studies, we found that it worked quite well in this collection of studies which also included observational studies. Authors of future publications could consider reporting items that help readers to assess the risk of bias by addressing the items in this instrument.

Finally, this systematic review solely includes peer-reviewed scientific literature. It therefore does not include military or other government technical reports that are not published in scientific journals. In the field of diving medicine and research, substantial experimental research has been conducted by military and government agencies outside traditional academic journals, its inclusion would provide a more complete overview of currently used ultrasound protocols.

FUTURE RESEARCH ENDEAVOURS

Based on our findings, we recommend that future research (1) as per the 2015 consensus, adopt standardised post-dive measurement timing schedules relevant for the corresponding diving profile, (2) implement standardised and clearly reported provocation manoeuvres, (3) improve data reporting by including individual-level bubble grades and applying appropriate statistical methods, and (4), provide detailed documentation of both operator expertise and ultrasound hardware specifications.

Conclusions

This systematic review demonstrates that, although two-dimensional ultrasound is widely used for post-dive VGE assessment, methodological heterogeneity remains. The

most common shortcomings included measuring for less than two hours post-dive, underreporting operator expertise and ultrasound hardware specifications, limited availability of individual-level data and inappropriate statistical treatment of ordinal outcomes. Furthermore, nearly all studies restricted imaging to the heart, thus leaving peripheral vessel assessment largely unexplored.

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