Technical report

First impressions: Use of the Azoth Systems O'Dive subclavian bubble monitor on a liveaboard dive vessel

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Bubble detection; Bubbles; Decompression; Recreational diving; Risk assessment; Surveillance

Abstract
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Introduction: The Azoth Systems O'Dive bubble monitor is marketed at recreational and professional divers as a tool to improve personal diving decompression safety. We report the use of this tool during a 12-day dive trip aboard a liveaboard vessel.
Methods: Six divers were consistently monitored according to the user manual of the O'Dive system. Data were synchronised with the Azoth server whenever possible (depending on cell phone data signal). Information regarding ease of use, diver acceptance and influence on dive behaviour were recorded.
Results: In total, 157 dives were completely monitored over 11 diving days. Formal evaluations were only available after six days because of internet connection problems. Sixty-one dives resulted in the detection of bubbles, mostly in one diver, none of which produced any symptoms of decompression illness.
Conclusions: The O'Dive system may contribute to increasing dive safety by making divers immediately aware of the potential consequences of certain types of diving behaviour. It was noted that bubble monitoring either reinforced divers in their safe diving habits or incited them to modify their dive planning. Whether this is a lasting effect is not known.

Introduction

Scuba diving exposes the diver to a certain risk of decompression pathology (decompression illness – DCI). Some forms of DCI are classified as 'barotrauma', related to compression or overexpansion of existing gas spaces in the body; 'decompression sickness' (DCS) on the other hand is (at least in part) caused by the formation of inert gas bubbles in tissue or blood vessels during and/or after decompression.[1,2] Regardless of the decompression algorithm used, detectable vascular gas emboli (VGE) may be detected after recreational, technical and professional diving;[3] the quantity of VGE is considered to be related to the risk of DCS after a dive.[4,5] Low VGE grades or absence of VGE after a dive are statistically associated with a safe decompression (low risk of DCS).[6] Even though in diving medicine research, VGE grades are sometimes considered an imperfect 'research endpoint' (as the ideal endpoint would be DCS)[7] it is at present accepted that VGE are an important tool for decompression physiology and safety research.[6,8]

Different methods of detection of VGE are possible: during field studies, bubbles are usually detected in the right atrium and pulmonary artery (acoustically, using Doppler or visually, using 2D cardiac ultrasound).[9] Various grading systems have been proposed, either categorical[10–12] or semi-quantitative.[13] Recently, detection of VGE in the subclavian veins has been re-evaluated and confirmed to correlate with DCS risk better than precordial monitoring. In (existing) dive databases with known outcome, subclavian monitoring was associated with high bubble grades (HBG) more than precordial monitoring when (and only when)

dive exposure severity was also accounted for (and for rest recordings only).[14] Based on this premise and building on novel biophysical modelling of decompression,[15–17] a simple 'self-measurement' tool has been developed and is currently marketed to recreational and professional divers. This tool, the Azoth Systems O'Dive sensor and app, guides the diver through a series of self-measurements, and after uploading the audio signals and related dive data to the Azoth Systems server, uses a proprietary algorithm to estimate the 'quality of decompression' (QI, which is inversely proportional to an estimated 'risk for DCS') for that dive. The algorithm is based on existing dive data (amongst others French Navy and Defence Research and Development Canada databases), but reportedly also builds on contributed O'Dive app data to continuously adjust and optimise the evaluation (Azoth Systems, personal communication). According to the O'Dive website, "*this allows scuba divers to personalise their diving practice by taking into consideration the gas microbubbles detected in their venous system after diving*". This 'retrospective view' of dive safety would then "*allow them dive after dive to improve their self-knowledge and to better anticipate their own body's reactions*".

The O'Dive app works with a connected ultrasonic sensor for bubble detection, which is linked to any iOS or Android phone or tablet by wireless connection. The sensor is simple and robust although not waterproof (IP54) (Azoth Systems, personal communication), and the sensor, ultrasound gel, mirror (for self-observation by the diver during the measurements) and wireless USB-C charger are contained in a small waterproof case.

This report will relate hands-on experience with the system during an actual dive trip in remote areas, in particular with regard to: the practical of use of the O'Dive system in real 'liveaboard' conditions, on multiple divers; some results obtained with the O'Dive system and how these were perceived by the divers; and adaptations made to the diving practice in response to the O'Dive results and their apparent effect.

Methods

This was a feasibility study, performed by DAN Europe research staff and volunteer divers during a dive cruise aboard a 'liveaboard' dive vessel, in the southern atolls area of The Maldives.

This study conforms to the Declaration of Helsinki and was part of a series of non-invasive bubble detection studies carried out by the Environmental, Occupational, Ageing (Integrative) Physiology Laboratory, Haute Ecole Bruxelles-Brabant (HE2B), Brussels, Belgium, approved by the Academic Bioethical Committee of Brussels (B200-2020-088). All divers received an oral explanation of the procedure, and the consequences of possibly detected bubbles were discussed beforehand. All participants were aware that, according to current scientific knowledge, the presence of bubbles does not indicate DCS to be present or imminent and does not need treatment if no symptoms of DCS are present. All divers were to dive according to their own dive plan, and no specific dive profiles were imposed. There was to be no interference with the group dive planning. All participants, experienced divers, gave written informed consent.

Diving was performed according to Maldivian law, which means: 'no deco diving' (no mandatory decompression stops), all dives less than 30 metres' seawater (msw) depth, less than 60 min, and surfacing with a minimum of 50 bars in the dive tank.

One person dived 'nitrox on air profiles' for increased security; nitrox tanks were limited, as due to a broken nitrox compressor they were filled when encountering other dive boats; all other divers used compressed air.

Several types of dive computers were used: Suunto D4i, Suunto D6, Suunto Zoop (RGBM algorithm), Mares Puck, Oceanic Geo (Buhlmann ZHL-16 algorithm). Average dive depths were around 25 msw, with an initial deep phase, then gradually ascending over 30 min to 10 msw, ending with a safety stop at 5 msw. Total dive times were mostly 60 min.

The O'Dive set consisted of an O'Dive One ultrasonic sensor with 2MHz wavelength (firmware version V6.08) and an iPad with the O'Dive One 'Vision' app (V. 1.8.42) (Azoth Systems, Ollioulles, France). The O'Dive set (a small waterproof case with the sensor and ultrasound gel, and an iPad in splashproof casing) were taken on board the 'dhoni' (small boat) dive vessel, and the first measurements were taken 10–20 minutes after exiting the water and taking off the dive gear. The second measurement was performed once back on the liveaboard vessel, respecting as much as possible the 30 min interval between two measurements.

The system requires measuring venous Doppler signals over the left and right subclavian vein, which then are counted as 'one measurement'. In short, the diver is instructed to, while seated and not moving, apply ultrasound gel on the sensor and place it in the subclavicular region, first on the left side. Visual instructions are displayed by the app. The mirror can be used to check the positioning (the primary intention is for the diver to perform the measurements on himself). Then, after confirmation that the sensor has been placed, the app displays an undulating line indicating the breathing-in and out rhythm to be followed, and a waveform pattern to check the signal quality. Once satisfied with the positioning, the diver can start the recording and this runs for 20 seconds. After this, the app indicates whether the recording was of sufficient quality to allow analysis, and if not, instructs the diver to repeat the measurement. Then, the right side is measured in a similar way, and once this is done, the app notifies that after 30 min a second set of measurements is

Table 1
Relevant data for participating divers. * = Nitrox used but computer set on air

Parameter	Diver 1	Diver 2	Diver 3	Diver 4	Diver 5	Diver 6
Age (years)	56	54	61	45	63	66
Sex	M	F	F	F	F	M
Body Mass Index (kg·m^2)	22.9	20.4	22.7	19.9	26	22.9
Dive experience (years)	35	35	40	29	35	40
Dive experience (dives)	1,500	800	2,190	2,000	1,100	3,800
Dive computer used	Suunto D4i	Oceanic Geo	Suunto Zoop	Suunto D6	Mares Puck	Suunto Zoop
Gas used	Air	Nitrox*	Air	Air	Air	Air

due. The diver then needs to input the depth, immersion time, dive duration, and stops performed in order to allow analysis. This permits the system to calculate the 'dive severity' as well as the timings of the two sets of recordings.

Whereas the app is conceived so that each diver can perform the measurements easily on him- or herself, for practical reasons all measurements were performed by one person (PG) on all divers, including himself. This allowed for a rapid succession of measurements and the 'investigator' to serve as time keeper for the second measurements.

Synchronisation of recordings must be performed with the Azoth server through Wi-Fi or cellular data. Analysis of the Doppler data is performed at the Azoth server side, and returned to the app upon the next synchronisation. Results are then presented in bar graphs, with the main indicator the 'quality of decompression' (Quality Index, QI) from 0 to 100, with colour codes (green: from 100 to 75; yellow: from 75 to 50; orange: below 50). The QI is lowered by two factors: a dive severity component (Cs) taking into the account the conservatism level of actual dive profile and a vascular bubbles component (Cb) computed from bubble counts, according to the formula QI = 100 – Cs – Cb.

Furthermore, the O'Dive app offers suggestions on how the QI of this dive could have been better, by simulating, for example, the effect of an extra or prolonged safety stop, the use of nitrox during that dive profile, etc. Because the app does not require the actual dive profile to be uploaded in order to allow evaluation, it is not entirely clear how these parameters are integrated in the O'Dive decompression model, only that the simulations "*are personalised by taking into account the vascular bubbles dynamics observed on your past dives which can evolve with the time*" (quoted from the app's help file and on the O'Dive website http://www.o-dive.com).

A 'tek' version of the O'Dive app is available', which includes the possibility to enter various gas mixes (bottom gas, decompression gas) into the data, select open or closed circuit diving, provide gradient factors, as well as allowing a link with some brands of dive computer to upload the actual dive profile. For the present evaluation, the 'O'Dive One' recreational version was used. The O'Dive 'Vision' software used was a special 'research' version that provided some form of a real-time monitoring system, in the sense that not only a Doppler waveform is displayed on the tablet, but also an acoustic signal of the heartbeat (from the neighbouring subclavian artery), breathing sounds and bubble sounds (heard as 'bubbly sounds' or clicks interspersed between the other audio). The 'public' version of the O'Dive app has the audio muted, and the displayed waveform is specifically treated as to not visualise the heartbeat and bubble signals, but only indicates by the waveform amplitude whether the sensor positioning is 'good' or 'suboptimal' (Azoth Systems, personal communication).

Evaluation of the O'Dive system's user-friendliness and diver acceptance was primarily subjective and impressions were collected throughout the dive trip from participant divers. A short questionnaire (using a modified Likert scale) was presented to the divers at the end of the trip, enquiring about their impressions.

Results

VGE DETECTION

Six divers were monitored over a period of 11 days. Demographic data are summarised in Table 1.

In total, 157 dives were monitored. For four divers, all dives were fully monitored, in two divers some data were missing (the second measurement of a dive was not performed for reasons unrelated to the device, such as the diver not being available due to lunch or other personal reasons). Monitoring several divers implied the creation of a separate account for each diver in the app, however switching between the various accounts was easy and fast, as the option to 'remain logged on' obviated the need to each time enter a password.

Positioning the sensor and recording the signals was straightforward, as the O'Dive app provides step-by-step instructions, and evaluates the quality of the recorded data immediately. If the signal is not sufficiently clear

Table 2
O'Dive data. Cb = vascular bubbles component of the QI; QI = dive quality index; VGE = vascular gas emboli

Parameter	Diver 1	Diver 2	Diver 3	Diver 4	Diver 5	Diver 6
Dives monitored	28	23	29	23	27	27
Mean QI	85	88	88	85	74	86
Dives with VGE *n* (%)	10 (36%)	7 (30%)	3 (10%)	11 (48%)	26 (96%)	4 (15%)
Mean Cb for dives with VGE	10.8	10.6	9.3	10.2	16.5	9.3
Mean Cb for all dives	3.9	3.2	1.0	4.9	15.9	1.4

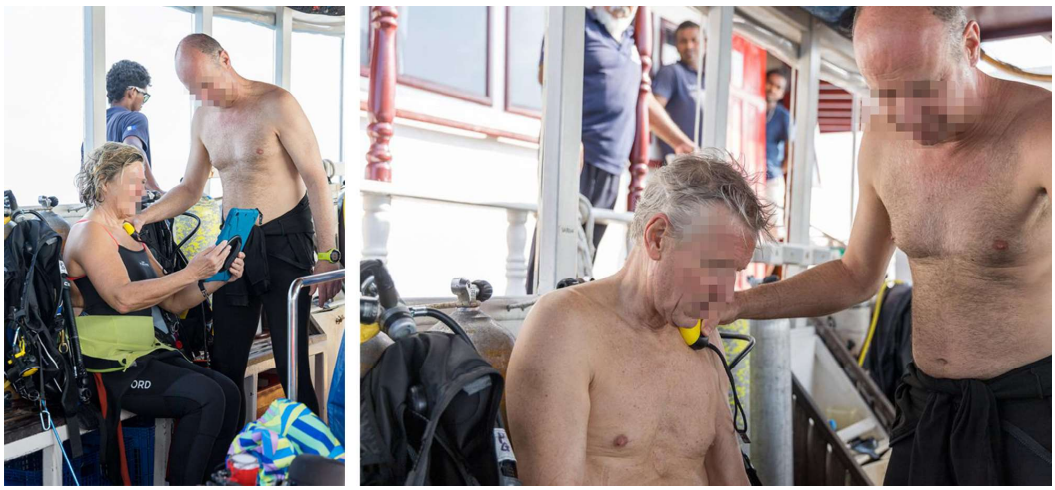
to allow evaluation by the O'Dive servers (for instance because of incorrect positioning), the app indicates that the measurement must be repeated because of 'low signal quality' or 'interpretation difficulties'.

During the first five days, no synchronisation with Azoth's server was possible because of low speed cellular data signal. After this, daily synchronisation was done, and each day, the analysis results of the previous day's dives was available, and was briefly reviewed by most of the participant divers (without detailed discussion).

Bubble signals were detected after 61 of the 157 dives (39%). In all divers, bubble signals were detected after some of the deeper or more strenuous dives, however, the O'Dive evaluation mostly remained 'green' (QI > 75) for all divers except one. In this diver (diver five), VGE were detected after virtually every dive (26 of 27 dives). In accordance with the intended use of the O'Dive system, adaptations were performed by that diver for subsequent dives such as more 'classical multi-level' dive profiles (deepest part first, followed by longer time at the 10 msw zone, followed by a safety stop). Further suggestions for improving the 'quality of decompression' offered by the O'Dive app (and visualised by simulating the modification alongside the actual analysis) were either to increase the safety stop duration (which would have necessitated a > 10min extension), to use hyperoxic mixes during decompression, or to dive nitrox for that profile (nitrox 32 would have increased the safety to almost maximal). This 'nitrox on air profile' suggestion was tested on one of the last dives (first dive of the day), and seemed indeed to result in an improvement of the QI (see Discussion). O'Dive data are summarised in Table 2.

Because of the small size of the test population and the lack of homogeneity, no clear correlation can be established between the number and frequency of detected VGE ('VGE dives' and/or Cb component) and biometric data. However, (female) diver four with the lowest body mass index (BMI 19.9 $kg \cdot m^{-2}$) had the second most frequent 'VGE dives' (11/23, 48%), though each time with a Cb of 10 or less and an average Cb of 4.9. Female diver five had the highest BMI (26.0 $kg \cdot m^{-2}$) and also the most frequent 'VGE dives' (26/27, 96%), with a Cb of 10 to 40, and a much higher average Cb of 15.9. Female diver two (with the second lowest BMI: 20.4 $kg \cdot m^{-2}$) used nitrox 32% as breathing gas while keeping the computer on 'air' setting ('nitrox on air profiles') for increased security because of a known persistent ('patent') foramen ovale (PFO), and had only seven 'VGE dives' (7/23, 30%). Using the simulation of the O'Dive app, if she would have been using air, not nitrox for these same dives, she would have had (according

Figure 1
Field measurements using the O'Dive system



to the Azoth model) VGE in 17/23 dives (74%) with an average Cb of 15.

EASE OF USE OF THE O'DIVE SYSTEM

The O'Dive system was found by the investigator (PG) easy to set up and use, even on the limited space of a 'dhoni' dive deck (see Figure 1). Switching between the various accounts to test different divers was straight forward and fast. Time to scan was typically less than 2 minutes per diver (20 seconds to prepare the sensor, 20 seconds per side). The tablet used was a regular iPad in a rugged splashproof housing. Over the test period, almost two flasks of ultrasound gel were used (400 ml) as well as six boxes of paper tissue.

DIVER ACCEPTANCE

Diver acceptance was very good, and none of the divers found the testing cumbersome or too time consuming. The results of the short questionnaire (modified Likert scale), while not formally validated, indicate that:

- The scanning after each dive was not considered bothersome;
- The procedure was considered simple and easy;
- The information obtained from the app was 'easy to understand';
- Most divers would not to adapt their next dive depending on the previous dive scanning (note that a formal O'Dive evaluation was only available the next day, with already two or three further dives performed);
- Diver five indicated that she adapted her general diving behaviour since being scanned (motivated by the O'Dive evaluation of her previous dives), and also indicated that she was feeling 'somewhat more stressed during the dives'. Indeed, some mental stress was noted immediately prior and during the scanning. This may have been due to the visual and acoustic indication that VGE were present, and it is for this reason that the public version of the O'Dive app does not disclose these indicators in real time (Azoth Systems, personal communication). The goal is to obtain a maximum acceptability of the method to all divers, not inducing extra stress (Azoth Systems, personal communication);
- Some divers considered a systematic scanning useful (but the questionnaire did not probe whether they would buy the system for personal use);
- One diver indicated that as a diving professional the system might be useful to monitor their personal exposure and take a day 'off' in case this exposure seemed to become too 'hazardous' (not further specified).

From an observer point of view, it was noted that using the O'Dive system generated multiple instances of discussing safe diving behaviour, the uncertainties of decompression theory and practice, and how to mitigate those. Divers with already 'safe' diving habits (e.g., performing systematic long safety stops, diving 'nitrox on air profiles') felt reinforced in this behaviour, and issues such as staying well within the no-decompression limit of the dive computer, the usefulness or uselessness of 'deep stops', how to prolong the safety stop and the advantages and risks of nitrox were all discussed in depth.

Discussion

VGE DETECTION

VGE incidence

The results confirm that after a significant proportion (61/157 dives, 39%) of recreational dives, VGE are detected,[3] even though all dives were performed well within the no-decompression limits of the dive computers used, all included a 3–6 min safety stop at 5 msw, and not more than three dives per day were made, with surface intervals never shorter than 90 min. Even though diving was performed in a group and all divers had, for each dive, (roughly) a similar dive profile as the other divers, there was a large inter-personal variability in numbers of VGE detected. Two of the divers almost never produced VGE (divers three and six), one diver had VGE after virtually every dive (diver five), and two divers had moderate amounts of VGE every 4–5 dives only (divers one and four) (data not shown). No external factors which could have led to a form of 'preconditioning'[18] were any different between the divers. While this is not a formal confirmation of previously reported inter- and intra-personal differences in VGE production[19] (as personal characteristics were not matched between divers), it is an interesting observation that in a single dive group, similar dives would lead to different VGE in different divers, and that the dive profile in itself might not always be correct in predicting 'the risk' of a dive.

Bubble grades

O'Dive bubble grades, as provided by Azoth after the end of the trip, were generally low (grade 0 to grade 1, except for diver five with regular grade 2's, two dives with grade 3 and one dive with grade 4 bubbles). No separate VGE detection method was simultaneously performed so a correlation between the O'Dive grading and other validated VGE grading methods, as recommended by Møllerløkken et al.[7] could not be established.

Although preliminary data from another dive trip, where O'Dive bubble grades were compared with 2D ultrasound recordings, show a good match between O'Dive grades and Eftedal-Brubakk (EB) grades (Costantino Balestra, personal communication), this lack of formal validation makes the O'Dive system as yet unsuited as a research tool. Until such formal validation takes place, access to the sound recordings (to perform actual bubble counts according to the Kisman-Masurel or EB scale) would be necessary for research. These recordings can be made available by Azoth (and actually were for the dives of this trip) but due to the

nature of the trip and the fact that the actual profiles of the dives were not recorded, a formal comparison is not intended at this point.

Dive behaviour modification in response to O'Dive data

Diver five had a consistently lower QI after each dive, and on many occasions bubbles were heard during scanning (Cb in the range of 20 to 40, consistently). Simulations from the O'Dive app suggested that using nitrox for each dive profile (i.e., 'nitrox on air') would have increased the QI ('safety') much more than performing longer safety stops. Because nitrox was not readily available, this diver modified her diving behaviour by optimising the dive profiles to be more straightforward 'multi-level' and increasing her safety stop duration. Near the end of the trip, as this did not seem to have much effect, it was decided to do a first dive of the day (dive 24/27 for this diver, with surface interval > 14 hours) with 'nitrox on air'. The O'Dive app was 'tricked' by indicating that this dive was still made on air only. Evaluation by the Azoth analysis later on indeed indicated an improved QI of 76 ('green') and a Cb of only 10, suggesting an effect of the reduced nitrogen load. The next three dives were again on air but still yielded 'green' QIs and Cb of 10 or less; this may have been the effect of a reduced inert gas accumulation (from that one nitrox dive) or just a coincidence (different dives), however, the sudden drop from Cb in the 20–30 range during the nine previous dives, was obvious (data not shown).

Diver two, using 'nitrox on air' for every dive, had VGE after some dives (7/23, 30%) and low Cb (average 3.2). The O'Dive app simulation indicated that, would she have been doing these dives on air, 74% of these dives would have generated VGE and the average Cb would have been 14.9, not 3.2. The QI would have decreased from average 89 to 64 (data not shown). Even though this simulation remains speculative (these air dives were not performed) it seems logical that a higher nitrogen load would lead to higher VGE counts in this diver and thus possibly a higher risk of DCS. In this regard, the O'Dive app simulation clearly stimulated this diver to continue using 'nitrox on air', even though subjectively she felt the dives were 'not very strenuous' and 'safe'.

The other divers indicated that they felt reinforced in their diving behaviour by the O'Dive evaluations. Diver six, a diving professional, stated that she might consider 'taking a day off' in case the O'Dive results would indicate an increasingly high VGE presence.

VGE and decompression sickness

Diver three had a long history of repeated DCS symptoms after diving (presenting as cutis marmorata and general fatigue), which was attributed to the presence of a PFO). Because of the impact on her diving pleasure (it occurred even after dives much less strenuous than the ones performed during this trip) and the ever-present risk of more serious DCS to occur, she had her PFO closed percutaneously four years ago. After this procedure, she had a complete absence of any symptoms following similar or even more strenuous dives. In this diver, because the closure of a PFO has no known impact on the propensity to generate decompression-related VGE, it was expected that VGE would have been detected after most dives (which did not arterialise through the PFO anymore, hence did not cause symptoms of DCS). However, no or very few bubbles were detected, and only after three dives (see Table 2). The O'Dive sensor's detection limit for bubbles has not been officially specified by the developers (Azoth Systems, personal communication), therefore it is possible that smaller-than-detectable bubbles were responsible in this diver for the regular symptoms of DCS prior to the PFO closure.[8,20] Alternatively, as the O'Dive sensor scans only the subclavian veins, it is possible that VGE were present but originated from the splanchnic or femoral vein territories[21] and thus were not detected in the subclavian veins.[14,22] As no simultaneous subclavian scanning and echocardiographic imaging was performed, this remains speculative.

DIVER ACCEPTANCE

Divers were able to recognise breath sounds, arterial sounds and bubble sounds (when obvious) on their own scan, and bubble sounds seemed to make a bigger impression than the colour graphs. None of the divers found the testing cumbersome or too time consuming. This may have been because they did not have to perform the measurements themselves and were only called to the scanning position when required by the investigator. A self-scanning procedure would undoubtedly have impacted more on their post-dive time management and thus on their overall experience.

The primary intended use of the O'Dive system is indeed to be a self-evaluation by each diver; however, the option of a scanning procedure to be offered by dive clubs or instructors to their clients is specifically mentioned by the manufacturers as a possibility.

STUDY STRENGTHS AND WEAKNESSES

This small field study was primarily intended to report on the real-world use of the O'Dive system, not to report on the safety of certain diving practices, or the accuracy or effect of using the O'Dive sensor and app. The participants were all experienced divers. It was felt that these divers would not be unduly impressed by the O'Dive app and hence modify their diving behaviour significantly at the slightest bubble detection, as this would possibly have placed an unacceptable stress on the diving group as a whole. It is possible the O'Dive system would appeal somewhat less to novice divers (it is not cheap, and some decompression physiology background knowledge is assumed).

Diver acceptance was probably slightly over-estimated as no burden was placed on the divers to do the measurements. The main investigator (PG) was experienced in the use of the system. Using a single investigator instead of individual divers measuring themselves was justified by the fact that only one O'Dive system was available, and that it was impossible to estimate the time needed to achieve all measurements on six divers after every dive. On the other hand, taking into their own hands the responsibility for the measurements could in some cases increase the motivation of divers to adopt a 'safer' behaviour.

The proprietary method of quality assessment and evaluation (mainly based on a number of doctoral theses only available in French) and the lack of validation between O'Dive bubble grades and other methods for quantifying VGE, make this tool (for now) unsuitable for proper dive research, even though the scanning procedure is very simple and quick.

The 'suggestions to increase dive safety' offered by the app's simulation function (prolonged safety stop, use of less nitrogen in the breathing gas for a similar profile) yield a 'factor of increased safety', which is visually attractive and easy to understand. However, it is based on a proprietary and non-transparent algorithm. Following these suggestions has not been demonstrated to result in lower rate of DCS (and relies on the statistical assumption that 'less VGE would result in less DCS'). This may possibly lead to a false sense of security.

Conclusions

The O'Dive system may contribute to increasing dive safety by making divers immediately aware of the potential consequences of certain types of diving behaviour. It was noted that this type of monitoring either reinforced divers in their safe diving habits or incited them to modify their dive planning. Whether this is a lasting effect is not known.

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