International Journal of Applied Technology & Leadership
ISSN 2720-5215
Volume 3, Issue 1, January 2024
ijatl@org

Integrating Alternative Ultrasound Technology into Saturation Facility Operations

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Abstract

It is widely accepted that the presence of venous gas emboli (VGE) is a necessary but insufficient condition for the development of decompression sickness (DCS) and that variability in physiological factors may contribute to DCS. With multiple organizations designing undersea saturation facilities that may see a substantial number of divers saturating, this creates an opportunity for the divers to volunteer as research participants to study the physiological factors influencing the inter-variability of VGE and DCS under identical dive profiles. Future large-scale saturation facilities will have an operations schedule that will make integrating VGE measurements more difficult than measurements during dedicated research dives. Alternative ultrasound technologies and methodologies should be explored to better integrate VGE measurements into busy operational environments and maintain continuous data collection. In this study, the O'DiveTM portable subclavian Doppler ultrasound was tested post-egress at Jules' Undersea Lodge, an undersea habitat at a six-meter depth, for usability and operations integration of a pilot study measuring potential physiological factors contributing to VGE variability. Two research assistants measured the VGE of seven divers who saturated inside Jules' Undersea Lodge and then rated the usability of O'DiveTM. The system received high usability scores and provided preliminary VGE data correlated with questionnaire data about lifestyle and physiological factors. The review and testing of O'DiveTM at a saturation facility showed that with additional bubble scoring validation, O'DiveTM could serve as a research tool for VGE measurements at future saturation facilities when operations prevent using gold standard VGE measurement methods.

Keywords: Saturation, Venous Gas Emboli, Subclavian Ultrasound, Hyperbaric Physiology

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1. Introduction

Multiple organizations have developed undersea saturation facilities for research, experiential education, and tourism. These habitats are designed to saturate divers at depth, where aquanauts live and work underwater. The specialized training of current and future aquanauts, high operational tempo, and integrated research programs for undersea habitats make future undersea saturation facility designs comparable to those of the International Space Station (ISS). Like the space station, a high volume of aquanauts may saturate within the facility, creating opportunities to utilize aquanauts as research participants while they conduct their planned operations. The controlled environment and identical saturation and decompression profiles would be ideal for studying inter-variability in the physiological responses to the hyperbaric environment.

Decompression sickness (DCS) is a known hazard when working within environments where changes in pressure are experienced, such as saturation diving. Risk factors contributing to increased probabilities of experiencing DCS include the dive profile, environmental factors, and physiological factors [1]. Studies that attempt to isolate the dive profile and environmental factors have shown that under the same dive profile and conditions, divers experience different decompression risks potentially due to physiological factors [1,2]. Identifying these physiological factors and determining personalized mitigation strategies for decompression sickness is a present area of research in hyperbaric physiology.

The gold standard method of decompression stress is measuring the presence of venous gas emboli (VGE) post-dive using Doppler ultrasound or two-dimensional echocardiography [3]. The 2016 consensus guidelines for the use of ultrasound for diving research outline these gold standard methods and include VGE grading, monitoring site selection, measurement durations, frequencies, and data reporting [3]. Once a VGE score is obtained, it is widely accepted that the presence of VGE is a necessary but insufficient condition for the development of DCS [4]. According to one chamber study with 1,322 participants, an absence of VGE post-dive negatively correlates with DCS symptoms and has a predictive value of 0.98 [5]. In the same study, the presence of VGE with grades of three or four had a positive predictive value of DCS of 0.39 [5].

Determining the physiological factors contributing to DCS requires controlling the dive profile and environment and then observing DCS symptoms or measuring VGE to estimate decompression stress. This places saturation facilities and undersea habitats in an ideal category for conducting VGE and DCS variability research. However, the dive operations, on-site training, and research support may be constrained at these operational undersea facilities. To conduct VGE measurements post saturation, a trained ultrasound technician must be on-site during the participants' egress, and the participants will be removed from other operational duties upon egress to obtain the VGE measurements. Once larger saturation facilities comparable to the ISS are built, research campaigns using Doppler ultrasound or two-dimension echocardiography are expected to be occasionally implemented into the facilities' operational schedule. However, if post-egress VGE measurements can be streamlined to be less invasive to existing operations and reduce research funding requirements through training reduction and on-site travel, lodging, and per diem costs for researchers, then a system could be implemented to obtain VGE measurements from every aquanaut egressing the saturation facility.

To obtain this higher number of research participants through operational integration of VGE measurements post-egress, research methodologies and technologies that reduce operational impact and costs should be considered at the expense of measurement precision. A similar operations integration issue for sleep and fatigue research was conducted on the space station. On the ISS, wrist-worn actigraphy sensors monitor the astronaut's sleep [6]. Although the gold standard for measuring sleep is polysomnography (PSG), and PSG has been used to measure sleep in space, actigraphy provides a less invasive and more convenient option to measure sleep, both to the astronaut and the operations schedule [6]. Validation studies have been conducted on actigraphy sensors to validate and develop corrections to best analyze actigraphy data compared to PSG. To date, over eleven thousand nights of sleep have been recorded from astronauts, including preflight, in-flight, and postflight data using actigraphy [6].

Like actigraphy and PSG, studies measuring post-saturation VGE at future undersea habitats should utilize the gold standard when feasible. Researchers should also consider other ways to validate and utilize sensors that may not provide as precise data but, like the actigraphy sensor on the space station, could be used more conveniently to support answering research questions without significantly interrupting operations. The actigraphy sensor equivalent for VGE measurements may be O'DiveTM by Azoth Systems or a future similarly designed product. O'DiveTM does not follow many of the consensus guidelines for the use of ultrasound for research diving. However, the last sentence of the guidelines states, "In the future, the guidelines may be refined and perhaps new methodologies developed for new and emerging technologies" [3].

1.1. O'Dive™ Portable Subclavian Doppler Ultrasound

O'Dive™ is a personal Doppler ultrasound that uses a proprietary algorithm to provide VGE information to divers soon after completing a dive to help improve diver decompression awareness and influence safe diving practice. It deviates from the consensus guidelines in several ways, including sensor position (subclavian versus precordial), bubble grading (proprietary algorithm versus a standard scale), and frequency of measurement (two measurements at thirty minutes and one hour versus the standard of two hours of measurements at twenty-minute intervals) [3]. Despite these significant deviations, O'Dive™ is beginning to be used and mentioned in scientific literature.

Peer-reviewed literature on O'Dive™ shows the system is usable during boat operations, obtains weak correlations with the VGE ratings obtained from gold standard methods, and is less sensitive than precordial ultrasound [7,8,9]. The difference between subclavian and precordial measurements and the lack of published validation of O'Dive™'s proprietary algorithm are two notable concerns about utilizing the system for research [9]. Although additional published validation is required, the established correlations between subclavian ultrasound VGE measurements and DCS make O'Dive™ a good candidate for decompression research when gold standard methods are not feasible [10,11].

The benefit of studying saturation divers is the dive profile and environment are controlled, allowing researchers to better determine what physiological factors contribute to VGE formation and, thus, DCS risk. Two published studies have mentioned the use of O'Dive^{TM} in saturation research. The underwater exploration program 'Under the Pole Expeditions' operated a small portable underwater "capsule" and saturated twelve divers. After decompressions, each diver's VGE was measured using O'Dive^{TM} [12]. The authors disclaimed, "Considering that the correlation between this device and the VGE score in two-dimension echocardiography is not clear, we acknowledge that this system was not the preferred method to assess saturation stress" [12]. Why the authors chose O'Dive^{TM} over echocardiography was not specifically stated. However, it is likely due to the convenience, reduced training requirements, and immediate feedback regarding decompression stress. The second saturation study that mentioned O'Dive^{TM} took place on a diving support vessel in the North Sea. The authors successfully used two-dimensional echocardiography to measure post-saturation VGE, although it was noted "after the decompression, due to operational constraints, it was difficult to "catch" the divers at regular times and some subjects (30%) only performed one or two of the four initially planned" [13]. Imbert et al. also called out O'Dive^{TM} in the conclusion, stating "Future experiments should include pressure resistance bubble measuring devices such as the O'Dive^{TM} system tool to ascertain a minimal bubble number in the subclavian vein during excursion dives and during decompression" [13].

To further test the possibility of embedding an O'Dive^{TM} sensor with a saturation facility's staff and standard operations to conduct a study on the physiological factors regarding VGE inter-variability, during this study, two research assistants were trained to use O'Dive^{TM} and completed measurements after the 24-hour saturation of two crews consisting of seven divers at Jules' Undersea Lodge in Key Largo, Florida.

1.2. Jules' Undersea Lodge and Marine Lab

Jules' Undersea Lodge is the former Puerto Rico International Undersea Laboratory and has been an undersea hotel since 1986. It is in a lagoon in Key Largo, Florida, and has a holding depth of six meters of seawater [14]. Due to the depth, saturating within Jules' Undersea Lodge incurs zero decompression penalty, and all divers visiting the lodge exit the facility and proceed directly to the surface after saturating. Despite dive tables showing no required in-water decompression when saturating at six meters, the VGE studies conducted at Marine Lab, an undersea facility that was once located next to Jules' Undersea Lodge, showed divers saturating at a holding depth of five to six meters had VGE after egress.

In one Marine Lab study, twenty-seven divers had a sixty percent VGE incidence rate using precordial Doppler ultrasound after saturating at five meters [15]. In a second Marine Lab study with thirty participants, sixty-six percent experienced VGE when measured using precordial Doppler ultrasound and seventy-three percent using subclavian ultrasound [16]. In a third Marine Lab study with a deeper holding depth of 6.25 meters, all twenty-three participants had VGE detected in the precordium using Doppler ultrasound [17]. The incidence of VGE

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measured during Marine Lab provides evidence that saturating at six meters at Jules' Undersea Lodge will result in measurable VGE in the divers.

2. Methods

The American Public University System (APUS) Institutional Review Board (application number 2023-090) provided ethics approval for this study.

Two research assistants were trained to use the O'DiveTM system and conducted Doppler ultrasound measurements, following the O'DiveTM user manual, on divers egressed from Jules' Undersea Lodge. The purpose of utilizing research assistants was to train divers to use the ultrasound system without needing to dedicate research support on-site at future undersea saturation facilities. The research assistants were both graduate students at APUS, and neither assistant studied decompression theory or hyperbaric physiology except for completing a SCUBA course. One assistant was open-water certified, and the other was advanced open-water certified. Training for both research assistants lasted approximately thirty minutes and consisted of a brief overview of decompression theory, human anatomy pertaining to the positioning of the sensor, how to take VGE measurements following the user manual, and one hands-on measurement for practice. The research assistants did not conduct the administrative set-up of the O'DiveTM application or accounts.

Following the measurements, both research assistants completed the System Usability Scale (SUS) questionnaire, quantifying their perception of sensor usability after only thirty minutes of training and in an operational environment. SUS consists of ten questions about the usability of a system. Each question is rated on a Likert scale from one to five, with one equaling 'strongly disagree' and five equaling 'strongly agree.' The System Usability Scale is scored on a scale of zero to one hundred, with higher values equaling greater perceived usability [18].

The seven research participants were a combination of students and faculty from APUS and the University of North Dakota who stayed overnight in Jules' Undersea Lodge for twenty-four hours while conducting independent research and outreach projects. Each participant completed a questionnaire on demographics, health, and selected lifestyle factors.

Upon egress from Jules' Undersea Lodge, a research assistant conducted ultrasound measurements on each participant at approximately thirty minutes and one hour post-dive following the O'DiveTM user manual. Four measurements were completed per participant, one per side (left and right) during each time block, with the participant sitting upright with no provocation. The O'DiveTM proprietary algorithm used these subclavian ultrasound measurements and the inputted dive profile to create a bubble component score rated from zero, meaning no VGE detected, to forty [19]. Participant demographics, health, and lifestyle factors from the questionnaire were correlated with the O'DiveTM bubble component score.

3. Results

The research assistants rated the usability of O'Dive™ highly. Using the System Usability Scale, one assistant gave O'Dive™ a perfect score of 100 out of 100, while the other gave it a 97.5, with the only markdown pertaining to the integration of the various functions of O'Dive™. The individual questions and responses are found in Table 1.

Table 1 Research Assistant O'Dive™ System Usability Scale Results

System Usability Scale Question	RA #1 Response	RA #2 Response
I think that I would like to use this system frequently.	5	5
I found the system unnecessarily complex.	1	1
I thought the system was easy to use.	5	5
I think that I would need the support of a technical person to be able to use this system.	1	1
I found various functions in this system were well integrated.	4	5
I thought there was too much inconsistency in this system.	1	1
I would imagine that most people would learn to use this system very quickly.	5	5
I found the system very cumbersome to use.	1	1
I felt very confident using the system.	5	5
I needed to learn a lot of things before I could get going with this system.	1	1
Total SUS Score (0 to 100)	97.5	100

Using O'Dive™, VGE was observed in the subclavian vein of three of the seven participants after egressing from Jules' Undersea Lodge. The bubble component score O'Dive™ used to express VGE is on a scale from zero to forty. Four participants had a score of zero, one had a score of three, and two had a score of six. No divers experienced symptoms related to DCS. The O'Dive™ bubble component scores were correlated with responses from the questionnaire using Pearson's correlations. The means, standard deviations, and correlations with VGE for each demographic, health, and lifestyle question are displayed in Table 2.

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Table 2 Demographic, health, and lifestyle questionnaire results and correlations with VGE

Demographic, Health, or Lifestyle Factors	Mean	Standard Deviation	Correlation with VGE
Height (cm)	174.4	7.7	-0.16
Body Weight (kg)	86.9	27.0	-0.09
Body Mass Index (BMI)	28.3	7.6	-0.04
Sex (correlated using Male = 1, Female = 2)	4 Male, 3 Female		0.28
Age (years)	36.7	8.3	0.18
Daily vegetable servings consumed.	2.9	1.5	0.68
Daily fruit servings consumed.	2.0	1.9	0.73
Daily dairy servings consumed.	1.1	1.1	0.04
Daily protein servings consumed.	4.1	2.0	0.71
Servings of protein that come from meat.	3.0	1.4	0.74
Daily grain servings consumed.	2.9	2.0	-0.28
Daily fat servings consumed.	2.6	0.5	-0.28
Servings of fat from unsaturated fat sources.	1.3	0.8	0.60
General perceived quality of diet (0 to 4 scale).	1.7	1.3	0.62
Weekly duration of aerobic exercises (min).	105.0	49.3	0.70
Weekly duration of strength-building exercises (min).	77.1	73.2	0.87
Weekly duration of flexibility and mobility exercises (min).	34.3	20.7	0.58
Weekly alcoholic beverages consumed.	1.1	1.1	-0.11
Days per week when smoke or vape.	0.4	1.1	-0.33
Clinically diagnosed with heart disease.	0.0	0.0	0.28
Clinically diagnosed with diabetes.	0.1	0.4	-0.33
Clinically diagnosed with hypertension.	0.1	0.4	0.13
Clinically diagnosed with high cholesterol.	0.0	N/A	N/A

4. Discussion

This study aimed to examine the usability of the O’DiveTM portable subclavian Doppler ultrasound system when integrated into the operational environment of an undersea saturation facility and provide evidence to pursue further validation and standardization of O’DiveTM for research. O’DiveTM was used to conduct VGE measurements of seven divers after saturating at six meters, and then paired the VGE data with a questionnaire to generate preliminary information on potential physiological factors that impact an individual’s risk of DCS. This methodology was useful for developing a research program at future undersea saturation facilities, considering it showed divers can be easily trained to conduct ultrasound measurements without on-site support from the investigator, conduct those measurements post-egress from a saturation facility, and then report high system usability scores. While Doppler ultrasound or two-dimensional echocardiography would be the preferred method for VGE measurement, O’DiveTM or a similar system could allow improved operational integration that allows for increased data collection that may not be feasible with other ultrasound systems.

With only a thirty-minute training session and the measurements conducted while multi-tasking with other operations, the research assistants rated the usability of O’DiveTM highly. With an average usability score of 98.8 out of 100, the assistants found O'DiveTM to be easy to learn, easy to use, not unnecessarily complex, and stated they would like to use the system frequently. The assistants, however, did not set up the O'DiveTM accounts, and the administrative aspects of the O'DiveTM application were not evaluated. While the convenience and ease of use make O'DiveTM an asset to data collection, the proprietary algorithm that detects and ranks VGE to generate the bubble component score is not readily available to researchers. It is difficult to compare and validate the O'DiveTM VGE measurements with established ultrasound data previously published in academic literature.

O'DiveTM's VGE measurements were correlated with the questionnaire responses, providing preliminary data about the correlations between VGE and physiological factors with each of the seven participants undergoing an identical dive profile in Jules' Undersea Lodge. With only seven participants, this data is preliminary, and conclusions should not be drawn. No correlation was present between VGE and Body Mass Index (BMI) or age, both commonly associated with heightened DCS risk. Moderate positive correlations were observed between a physically active lifestyle, total food consumption, and observed VGE. This contradicts the accepted notion that a healthy lifestyle prevents DCS risk. This result is likely due to a small research population and non-measured or analyzed potentially confounding variables. Ultrasound precision may have played a role in this deviation, showing the importance of further published validation of the O'DiveTM sensor.

5. Conclusion

This study aimed to determine the usability of O'DiveTM and collect preliminary data on the physiological factors of VGE formation using an operational saturation facility. After only thirty minutes of training on the system and collecting VGE measurements on seven participants, two research assistants rated the usability of O'DiveTM as 98.8 out of 100 using SUS. O'DiveTM proved highly usable and integrated well into post-egress operations at an undersea saturation facility. Although additional sensor validation is warranted, existing literature on O'DiveTM and similar measurements conducted in shallow water saturation dives shows a potential to use this sensor for VGE variability research when operational integration of gold standard methods are not feasible. To expand the data collection on the large number of aquanauts that may saturate at future saturation facilities and to improve our knowledge of hyperbaric physiology, O'DiveTM and similar systems should continue to be validated and standardized as research tools to be integrated into operational environments where the current gold standard VGE measurement methods are not continuously feasible.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Special thanks to the APUS Analog Research Group and Jules' Undersea Lodge for their support in planning and executing the 24-hour stay inside Jules' Undersea Lodge.

Funding: This work was supported by the American Public University System Graduate Studies and Research Office.

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