Int Marit Health
2023; 74, 1: 36–44
10.5603/IMH.2023.0004
www.intmarhealth.pl

ISSN 1641-9251
eISSN 2081-3252

VIA MEDICA

ORIGINAL ARTICLE

Scientific shallow saturation dive expedition using diving rebreathers and a specific dry habitat: medical management of the "Capsule" programme

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ABSTRACT

Background: *Scientific underwater exploration could benefit from professional diving facilities. This could allow marine research for durations far exceeding anything currently possible. The closed-circuit rebreather expansion provides new perspectives by unleashing divers and their diving bell. "Under the Pole Expeditions" developed an innovative compact underwater habitat for this purpose.*

Materials and methods: *The habitat's depth was fixed at 20 m. Saturation lasted 3 days and was followed by a 245 min long decompression procedure with mandatory in-water phase. Isolation and environmental constraints will require specific medical and safety procedures. "In situ" medical concerns were considered, and a specific evacuation plan was established. This report describes the medical management of this atypical project and the systematic clinical follow-up mostly targeted on the cardiovascular system, fatigue and psychological tolerance.*

Results: *Seventeen individual saturation exposures were performed. All selected divers were professional. Neither severe illness nor decompression sickness was observed. These short-term saturation exposures appeared to be well tolerated. There was a relatively low bubble grade after decompression. Psychological tolerance appeared good. However, a transient moderate orthostatic hypotension suggested cardiovascular deconditioning after dive.*

Conclusions: *This first experiment demonstrates the interest and feasibility of a shallow revisited saturation dive with rebreather use. This isolation requires medical accompaniment and rigorous preparation. Medical and physiological risks assessment is essential in this context and must be consolidated by new experiences.*

(Int Marit Health 2023; 74, 1: 36–44)

Key words: risk management, diving at work, decompression tables, pressure chambers, helium, oxygen

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Received: 7.12.2022 Accepted: 11.01.2023

INTRODUCTION

In the second half of 20th century, we saw birth of undersea habitats and accordingly saturation diving expansion. The first 'serious' undersea habitats were conducted by Edwin Link and Jacques-Yves Cousteau in 1963 with the "Man in Sea" and "Precontinent I" programmes, respectively. Their projects have paved the way to deeper and longer undersea exploration. However, budgetary constraints have restricted the undersea habitat's democratisation.

In contrast, with bounce dives, staying at pressure for a long time will lead to saturation diving. Divers live in dry hyperbaric complex chambers. They work in water linked to their pressurised diving bell. Their whole body is saturated at equilibrium with partial pressure of inspired gases. The decompression time for a given depth is at a maximum and will not increase with additional time at depth. The objectives are to decrease physiological stresses and increase work efficiency index [1]. The French company COMEX^SA, in collaboration with the French navy, has been a pioneer in the development of saturation diving. Their research topics were focused on different gas mixtures with current records in open seawater at 534 msw and in simulated dry chamber at 701 msw [2]. Currently, saturation diving is considered safe and effective. Responses to stressful conditions have been documented using various physiological, biochemical, and psychological measures [1]. The complexity and cost of these facilities restrict use for industrial purpose. Other fields, like marine biology, could benefit from these technological advances.

A French underwater exploration programme "Under the Pole Expeditions" combines scientific research, innovation and awareness to better knowledge and ocean preservation. This team carried out this original saturation project during its third expedition (2017–2021) in an ambitious marine biology coral-reef programme. They developed a small portable underwater "Capsule" to perform research for durations far exceeding anything currently possible. Divers will be able to live several days underwater and to move freely around with SCUBA gear while commercial divers are restricted by their umbilical.

This paper describes the "Capsule" programme with technical and diving procedural aspects followed by the medical management and perspectives.

MATERIALS AND METHODS

In preventive consideration and the need to early detected any adverse effect, a rigorous large clinical medical examination of each diver seemed imperative [3]. This was performed in accordance with usual clinical practices in diving medicine by the medical team. All divers were informed about the potential risks and discomforts associated with this programme and gave their consent prior to beginning. All medical data were collected and analysed to follow-up health status in accordance with the Helsinki Declaration [4].

TECHNICAL SPECIFICATIONS AND OPERATIONAL MANAGEMENT

The habitat needed to be simple, light, compact, safe and relatively autonomous. Under the Pole and its engineering office designed and made this "Capsule" and its specific electronic system (Fig. 1). It is about 5-times more confined than professional complexes. A Wi-Fi floating buoy was linked to the capsule. Direct video, audio transmission and monitoring data were sent continuously to an onshore control centre, which is located at 2.2 km. This programme took place in October 2019 in Moorea Island, French Polynesia. Ambient temperature inside the Capsule was 29 °C with hygrometry at 90%. Water temperature was 27 °C. Divers used JJ-CCR rebreathers DiveCAN® (JJ-CCR ApS, Presto, Denmark) for their excursion dives. In water, divers wore neoprene 5 mm wet suit with a hood.

Single decompression procedure after multiple excursions is the main interest in such a saturation programme. Under the Pole, in conjunction with decompression specialists, created specific diving procedures. The purpose was to achieve multi-day stay under pressure allowing for continuous marine life research. In operation, the 'Capsule' cannot be mobilised and there is no wet bell. Therefore, in-water decompression was mandatory. A 20 msw depth was determined with a maxi-

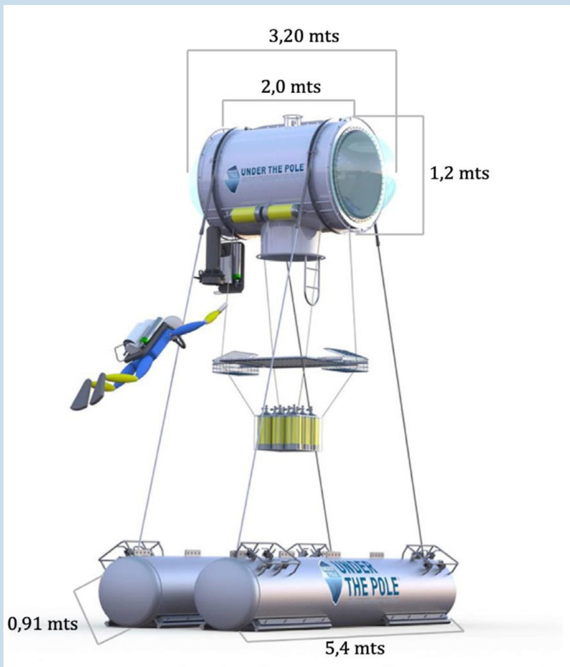

Figure 1. Technical drawing of the submarine habitat "Capsule" designed by Under the Pole Expeditions. The "Capsule" is a cylinder of 4.5 m^3 fitted with two domes and a below access lock. Continuous gas monitoring allows electronic fine adjustment of oxygen partial pressure. Metabolic production of carbon dioxide is removed by soda lime and other gaseous contaminants by activated charcoal

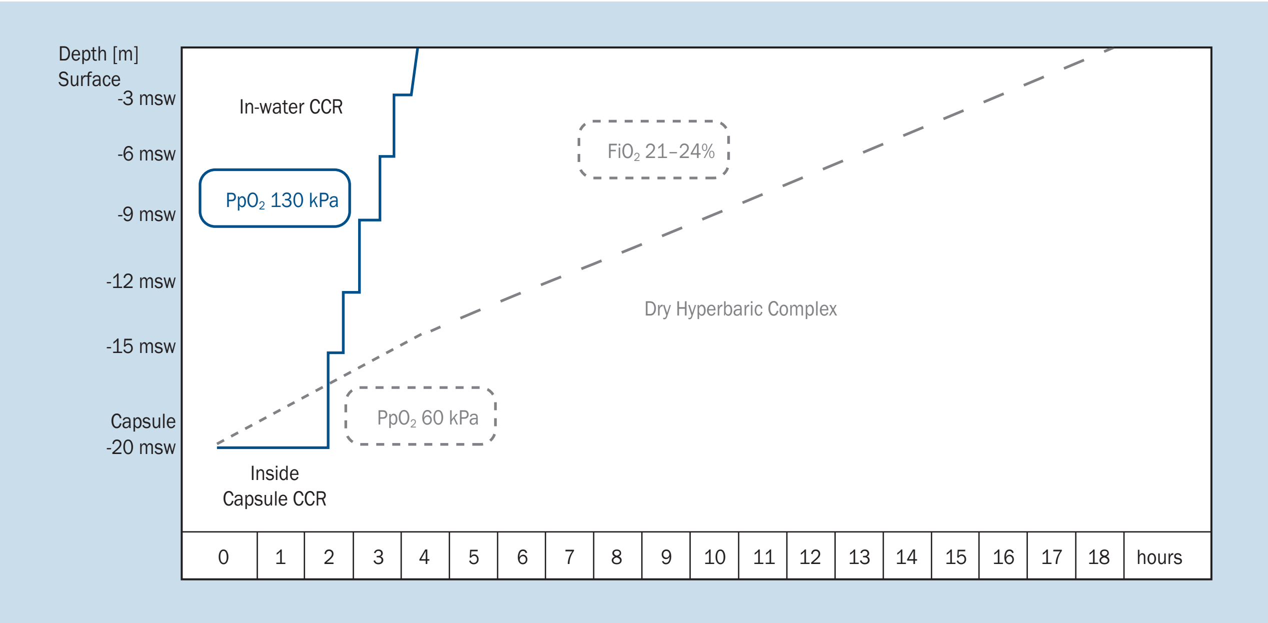

Figure 2. Final decompression procedure. It began by a 2-h pre-oxygenation in the "Capsule" followed by linear in-water decompression (solid blue line). The dotted grey line represents final decompression procedure for helium-oxygen saturation by table of French Ministry of Labour (1992); CCR — closed circuit rebreather

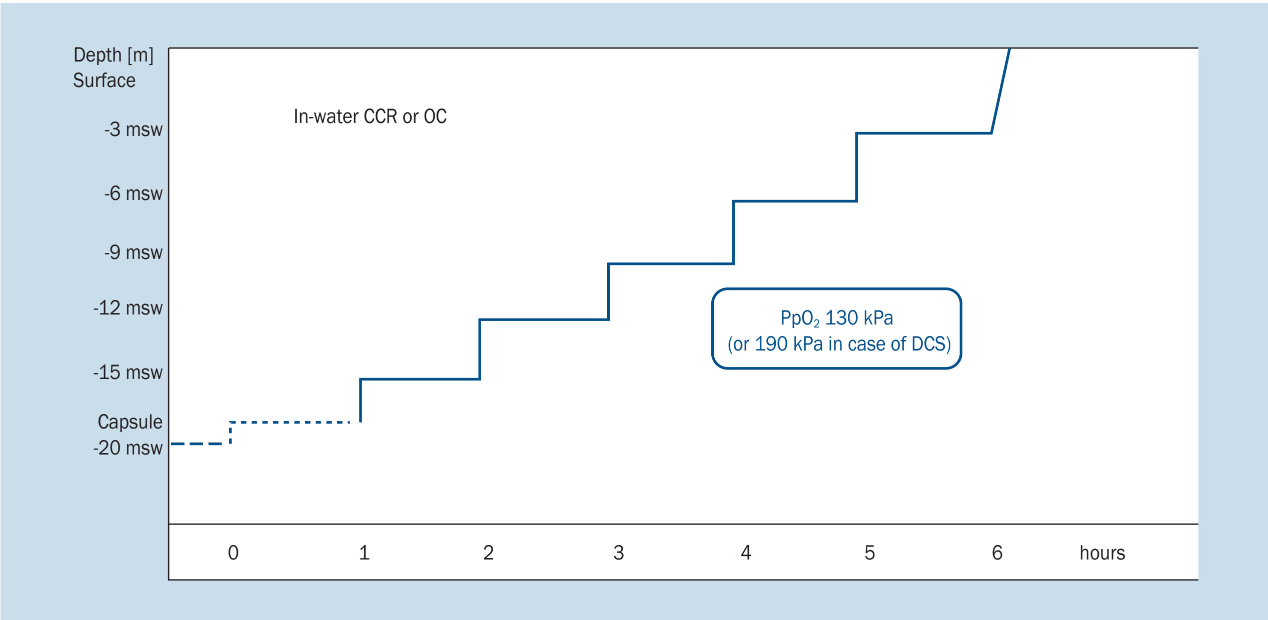

Figure 3. Final emergency decompression procedure. The solid line represents the final emergency decompression procedure. The dotted line represents an optional first one-hour stop at 18 msw in case of severe decompression sickness (DCS); CCR — closed circuit rebreather; OC — open circuit (safety tanks)

mum length of 3 days at depth. The breathing atmosphere was composed by a helium-oxygen gas mixture. The environmental PpO_2 was maintained at level of 40 kPa as it occurs in commercial diving [1]. Rebreather with usual setpoint at 130 kPa was used for excursion and decompression [5]. Excursion dives were allowed between 15 and 36 msw without decompression requirement to reach the habitat.

The "final decompression procedure" is shown in Figure 2. This decompression protocol was used during the whole saturation programme. It resulted in a total time decompression of 4 hours. If dry pre-oxygenation could not be done (e.g. major technical trouble, unbreathable atmosphere...), an "emergency procedure" provided a 5-hour in-water decompression in five one-hour stops (Fig. 3).

Each diver had a little scuba tank inside the capsule for an emergency evacuation. Three safety lines fitted open scuba cylinders with optimal gas mixture were located near the "Capsule". This allowed final decompression in case rebreathers were not useable.

MEDICAL AND SAFETY CONSIDERATIONS

A medical team was associated with this project for safety procedure management. In expedition medicine, prevention represents one of the keystones to minimise risk [3]. Nevertheless, risk reduction could not exclude all dangers and illnesses from arising. Access to definitive medical care involves prolonged evacuation over many hours due to mandatory decompression.

Barotrauma and decompression sickness (DCS) appear to be the most common bounce diving related injuries [6]. However, staying in closed, wet and helium hyperbaric environment for a long time would expose to inherent health problems, such as fluid balance and haemodynamic dysregulation, infectious risk, hypothermia, nutritional aspect or psychological intolerance [1]. Traumatic injuries or accidental toxic exposure also had to be envisaged. Specific risks with autonomous rebreathers may occur like biochemical accident or loss of saturated diver who does not reach the habitat [5, 7].

Diver selection

All divers were recruited by the expedition's leader. They were trained rebreather scientific deep-divers. None had experienced saturation dives before. None had chronic illness or took medication and they were medically fitted to dive.

Safety and medical management

For excursions, divers were accompanied by bounce divers and visibility was always clear which limits the risk of getting lost. Rebreathers were refurbished (gas and soda lime) and tested every day by the surface team. In dive, particular attention was paid to fluid intake with unrestricted access to drinking water. Moreover, fatigue and diet may have a significant impact in saturation tolerance [8, 9]. Rest periods were mandatory and three individual retractable bench seats were available. The caloric intake was increased. Divers could seek medical advice at any time.

At saturation, decompression is a compulsory phase resulting in poor health outcomes if not completed. Considering this, the medical team had to be able to manage any medical incidents inside the "Capsule" for the primary care and stabilisation before through-water evacuation. A first care pharmacy with usual oral drugs (analgesics, antiemetic, anti-vertigo, antiseptic, bandage...) was inside and could be used with medical advice. Furthermore, an intensivist and hyperbaric physician was in the safety divers' team. Various submersible medical kits and supplies were available, depending situation (intravenous access and fluid, second-line medications, urinary catheter or chest tube...). Due to limitations in acute care capabilities, we focused on the most likely and severe conditions [3].

Decompression sickness becomes a rare occurrence in saturation dives. However, acute muscular and joint pains or, less likely, vestibular manifestations have been shown [1, 10]. Depth at 20 msw allowed accessibility for logistics and rescue. If symptoms appeared, the "Capsule" would have been firstly used for hyperbaric oxygen therapy with rebreather (to reduce atmosphere contamination) to maintain manually PpO_2 near 280 kPa as in therapeutics with pure oxygen breathing. The therapeutic processes depending on circumstances of occurrence are available in Supplementary Appendix (see journal website). After a few hours of inside care and medical evaluation, in-water decompression is envisaged. This is based on an "emergency procedure" for 5-to-6-hour durations with an elevated PpO_2 of 190 kPa considering the therapeutic approach [11, 12]. Rebreather use with mouthpiece head-strap was preferred but open-circuits SCUBA with facial mask or regulators were available on the safety line.

For this atypical in-water primary care request and extended timeline, a specific emergency evacuation plan was provided upstream to local health authorities. Medical care facility including hyperbaric chamber was available less than 1 hour after surfacing with helicopter evacuation. All medical evacuation procedures were simulated and practised. Inside oxygen administration with rebreather was tested for several hours, without significant change in the composition of atmosphere. The "emergency decompression procedures" with a five-hour in-water decompression were also tested.

Methods for medical assessment

For the medical team, the purpose was to assess the health condition of divers during this specific programme. The medical assessment was performed prior to diving, 1 hour after surfacing and at 24 hours after surfacing. Based on the expected health implications, this thorough medical check-up mostly targeted the cardiovascular system, fatigue and psychological tolerance [1, 8, 13].

To ensure haemodynamic tolerance, non-invasive arterial blood pressure (ABP) and heart rate were measured at rest in supine position with multi-parametric monitor Datex-Ohmeda S/5 (GE Healthcare, Vélizy Villacoublay, France). To test orthostatic tolerance, heart rate and blood pressure were measured with divers in the supine position after 10 min rest and then upright at 5 and 15 min after rapid standing up. This test was performed for the last 8 expositions following a standing-up severe hypotension associated with syncope arising in one diver. Considering that body fluid balance can be evaluated by body mass loss, body weight was measured with an electronic balance [14].

To detect any sign of emotional distress, a self-reported mood survey was administered daily to each diver. The Positive and Negative Affect Schedule (PANAS) form was developed to provide brief measures of positive (PA) and negative affect (NA). A 5-point scale is used for scoring items and reveals the importance of each affect. Low level of NA indicates a state of calm and serenity, whereas high level of NA is a characteristic of anxiety [15]. Furthermore, medical interview allowed to report psychological or physical well-being or any other complaints. They were not quantified and will be anonymously summarised.

Divers could self-measure their decompression tolerance in bubble monitoring by a commercial connected ultrasonic sensor O'dive system (Azoth Systems, Ollioules, France) on bilateral subclavian vein at rest in the sitting position at 30, 50 and 100 min after surfacing [16]. Venous gas emboli (VGE) detected by this device are often quantified as a marker of decompression stress. VGE were graded from 0 to 4, according to Spencer scale and considering the peak value [17].

STATISTICAL ANALYSIS

Statistical analysis was performed with GraphPad Prism v9.0.2 (GraphPad Software Inc., San Diego, CA, USA). All data are presented as median (1st and 3rd quartile). Normality of distribution is assessed by Shapiro-Wilk test. ANOVA for repeated measures is used to analyse more than two related groups followed by multiple comparison Tukey's post-hoc test. Statistical significance was set at $p < 0.05$.

RESULTS

Eleven males and one female successfully completed saturation dives in groups of two or three divers. On average two excursions of 30 min each per day, with a maximum depth of 35 msw, were performed. Five divers did two stays with a minimal 15 days interval between each saturation. This represents 17 individual expositions. Table 1 presents demographic data.

There was no acute illness except in one diver who suffered headache after the first night linked with inadequate fluid intake. Favourable outcome was observed after hydration and oral analgesia allowing the continuation of the saturation dive.

None of the divers developed any symptoms of DCS during or after dives. After surfacing, all divers performed bubbles monitoring. The bubble grades did not exceed grade 2 except one diver who presented a transient grade 3 (Fig. 4).

Table 1. Demographic data of the participating divers (n = 11)

	Median [Q1;Q3]	Min–Max
Age [years]	37 [29–39]	26–61
Height [cm]	182 [176–86]	168–200
Weight [kg]	73 [67–77]	56–92
BMI [kg/m^2]	21.5 [20.9–24.8]	19.4–28.1

BMI — body mass index; Min–Max — minimum–maximum

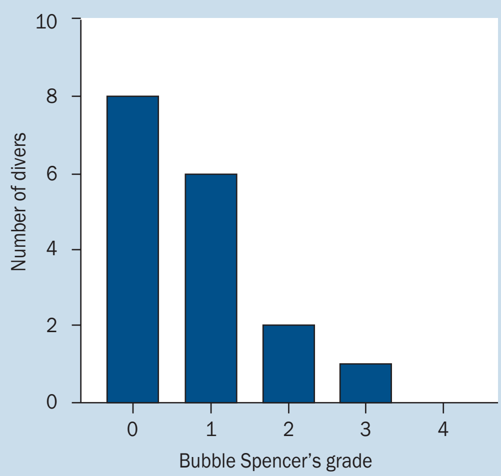

Figure 4. Maximal vascular gas emboli after surfacing according to Spencer's grades. Post dive bubble self-monitoring with peak value on bilateral subclavian vein (n = 17)

Systolic ABP showed a tendency to decrease after the dive which did not reach statistical significance (p = 0.05). No change was found in diastolic or mean ABP. Orthostatic tests showed a significant difference in systolic ABP (p = 0.03). In post hoc analyse, ABP measured at 5 min of upright position was lower than initial measurement with –9 [–7; –21] mmHg (Fig. 5). This orthostatic decreasing ABP was neither shown before dive nor at 24 h post-dive. A significant body mass loss with –1.4 [0.6; 2.3] % of total body weight was shown just after surfacing ($p < 0.0001$) with a baseline return at 24 h (p = 0.6) (Fig. 6).

The PANAS indicated no change in PA (p = 0.1) but a significant decrease in NA (p = 0.0001). From the second diving day, NA score was lower than baseline in post-hoc analyse and remained after surfacing (Fig. 7). Apart from one diver describing a brief migraine after his two stays, no other complaints were reported during medical review. Confined living space and workload caused a certain "self-reported" level of fatigue that divers considered compatible with their mission. There were no reports of sleep disorders or thermal discomfort except during the long in-water "emergency decompression procedures" test.

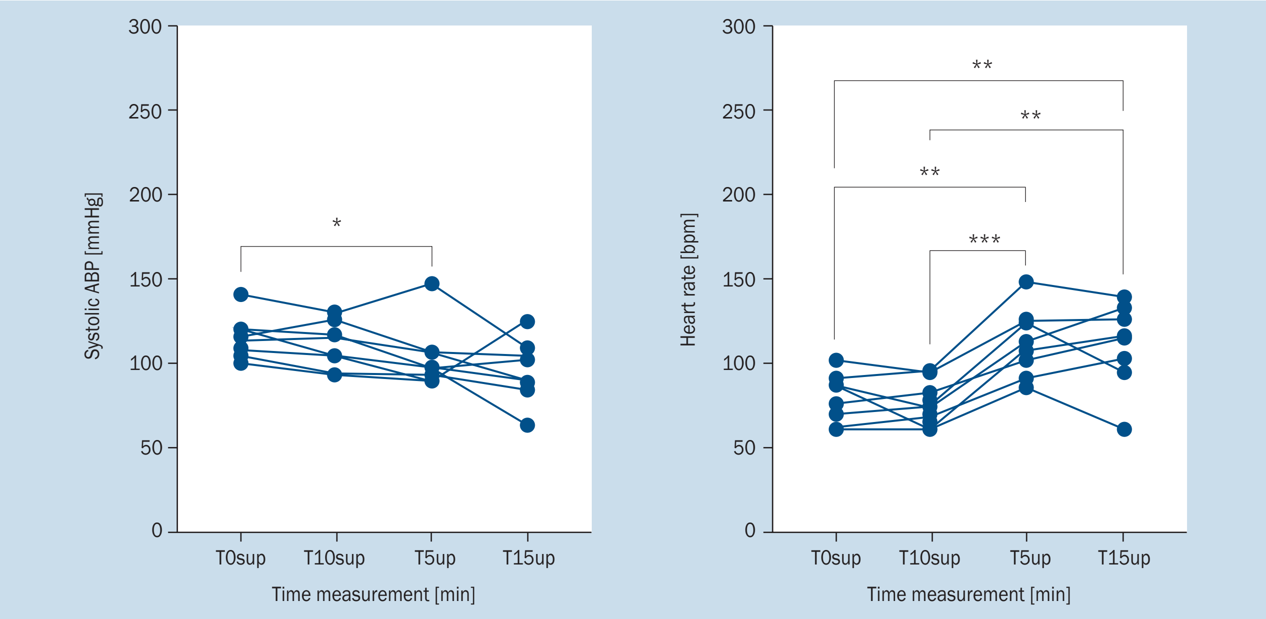

Figure 5. Variation of systolic arterial blood pressure (ABP) and heart rate in orthostatic test immediately after surfacing; Sup — at rest in supine position; Up — after standing up in upright position; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

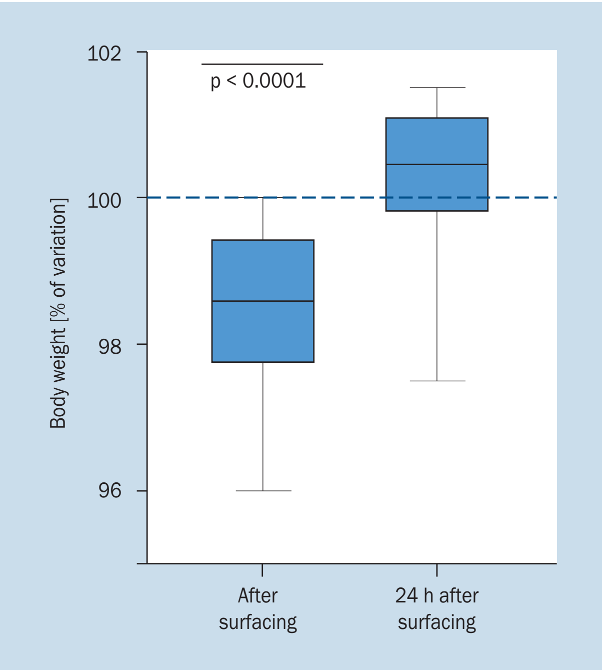

Figure 6. Percentage of body mass variation after surfacing. Variation of body mass is expressed in percentage versus predive measurement

DISCUSSION

This innovative scientific diving programme was successful. All marine biology projects were led without any major technical or medical incident during multi-day underwater stays. Fortunately, no evacuation from the capsule was necessary. From medical point of view, this first report shows the feasibility and relevance of this type of habitat, but we cannot conclude extensive outcomes to general population and other habitat's configuration (location, depths or dive time). Medical follow-up was reassuring without significant symptoms of poor tolerance.

Absence of any signs of DCS and the medical follow-up appear to show a good clinical tolerance of the decompression. All divers had a low bubble grade except one with grade 3 without clinical symptom. Although the physiopathological mechanisms of DCS are still debated, VGE and DCS occurrences are associated with positive correlation [18, 19]. Most studies indicate this correlation is also true in saturation diving but DCS cases not accompanied by VGE seems to be higher than for bounce diving [10]. The O'dive is a new self-measurement device. It allows a simple and fast testing procedure. It makes divers immediately aware of the potential consequences of decompression. However, considering that the correlation between this device and the VGE score in two-dimensional-echocardiography is not clear, we acknowledge that this system was not the preferred method to assess saturation stress [16, 20]. This would require additional precordial measures and a greater number of subjects to validate the "decompression procedures" used during this programme. Helium is usually used to dive deeper than 50 msw. It is more diffusible and had low solubility. The use of oxygen-helium mixture despite the shallow depth allowed a manoeuvrable decompression and faster than with nitrogen. The "decompression procedures" considered that speed rate is determined by the oxygen concentration [21]. However, oxygen may be toxic with acute neurological toxicity and long-term effects on lungs [22]. This model driven by oxygen appear effective as previously suggested by Kot

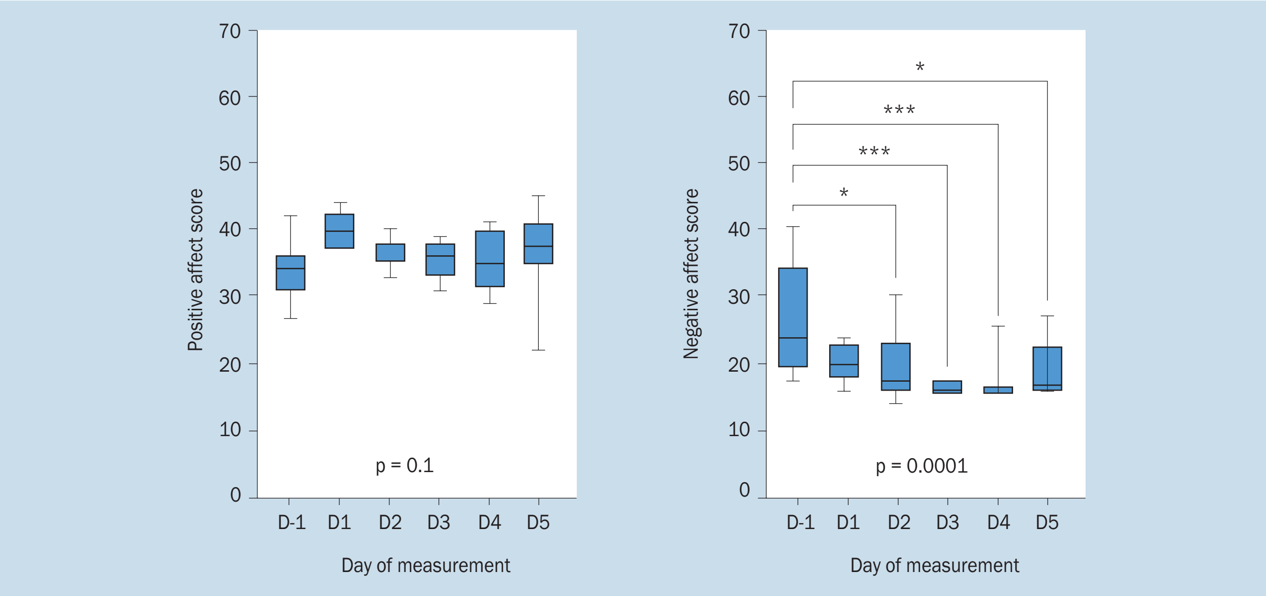

Figure 7. Positive and Negative Affect Schedule (PANAS) survey score during and after dive. D-1, D4 and D5 were performed at surface before and after dive. Measurements between D1 and D3 were performed during saturation dive; *$p < 0.05$; ***$p < 0.001$

et al. [23] in Nitrox saturation dives or Blatteau et al. [24] without VGE detection and non-significant spirometric alteration. Procedures were based on the COMEX database which allowed the development of regulatory procedures in professional diving in France and the REPEX oxygen toxicity threshold [22, 25]. However, the cumulative oxygen limits could be exceeded for deeper or prolonged dives with special consideration for pulmonary toxicity. In the therapeutic approach at 20 msw, pure oxygen breathing is close to what is used therapeutically with a low risk of hyperoxic seizure. Electro-galvanic oxygen sensor capacity is exceeded at this PpO_2 and manual oxygen adjustment without monitoring would be impractical for a deeper habitat.

Examination after the dives suggested cardiovascular deconditioning like it is described in microgravity. This cardiovascular deconditioning is demonstrated by haemodynamic changes and reduced exercise capacity [26]. Cardiovascular homeostasis involves autonomous nervous and neuro-endocrine systems. Orthostatic hypotension is defined as a reduction of systolic ABP > 20 mmHg or diastolic ABP > 10 mmHg after standing up [27]. Thus, after surfacing our divers had moderate delayed non neurogenic orthostatic hypotension with abnormal heart rate acceleration. The exposure in saturation dive at 46 and 37 ATA had already shown reduced plasma volume and evidence of this orthostatic intolerance [13]. Considering that dehydration plays a role in decompression stress, hydration was favoured to limit these effects [28]. The body mass loss just after surfacing suggests a moderate negative hydric balance. Divers lived in a very confined space without possibility to stand upright inducing a ‘bed rest’ effect [29]. The transient cardiovascular deconditioning in this shallow programme will be considered for prolonged or deeper mission.

Divers seemed enthusiastic about their experience according to PANAS psychometric testing, a widely used clinical measure [15]. Our results did not show any sign of anxiety during this short-confined exposition. All divers were selected and actively engaged in this programme. Conversely, many studies report a negative impact on emotional stability during long saturation dives and shift-work. Data show substantial increase in fatigue and hostility with an accompanying decline in perceived well-being [1]. A 7-day shallow nitrox saturation dive has shown reduction in total sleep time and efficiency. Authors suggest that these changes were related to long stays in a confined environment and not by environmental pressure [30]. Sleep disorders could also be a trigger of headaches reported by divers. These aspects will demand special attention for longer stays in this very confined habitat or if a wider non selected population have to stay (e.g. scientists or other professionals).

In this specific tropical environment, divers did not experience thermal discomfort except during the “emergency decompression” test. In case of DCS, prolonged in-water decompression would have required adequate thermal protection in dry-suits with a heating system which could be brought to the “Capsule”. These data are reassuring but could not be transposed into more temperate waters in the absence of a specific protection system for divers and the habitat. Thermal protection would be an important challenge in another environment.

Finally, physiological short and long-term evaluations would be necessary to fully assess this new approach of diving procedures. The main limitation of our report is the small sample of selected professional and fit divers. The excursions carried out had very conservative and short duration. This could be explained by spontaneous limitation to stay in safe areas of procedures because that was the first saturation experience for divers.

CONCLUSIONS

This innovative habitat allows performing research for durations far exceeding anything currently possible. Under the Pole demonstrates the interest and feasibility of saturation dive methods using rebreather. Medical consideration is essential in this context of in-water interventions which does not allow an immediate return to the surface in case of emergency. That requires medical accompaniment and rigorous preparation. A medical plan with an ability to operate directly underwater must be absolutely considered because of the high level of isolation. Other saturation experiments with divers monitoring seem necessary to validate these procedures and the field of exploration offered by this new type of scientific dive concept.

ACKNOWLEDGEMENTS

Authors thank all the team of “Capsule” programme, and particularly Ghislain Bardout and Emmanuelle Périé-Bardout, co-founders and director of the Under the Pole Expeditions, who have enabled the development of this innovative programme. We thank Dr. Julien Hugon, scientific director of Azoth system, for his assistance for US signal analyse. We thank Dr. Bruce D’Souza for his assistance and advice in manuscript revision.

FUNDING

“Capsule” programme was initiated by Under the Pole, SAS. Technical development and logistic was supported by its own funds. The described medical supervision did not receive external funding.

Conflict of interest: None declared

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