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ORIGINAL ARTICLE

Evaluation of North Sea saturation procedures through divers monitoring

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ABSTRACT

Background: *Saturation diving is a standard method of intervention for commercial diving during offshore operations. Current saturation procedures achieve a high level of safety with regards to decompression sickness but still put the divers under multiple stressors: 1) Environmental stress (long confinement, heat/cold, dense gases, high oxygen levels), 2) Work stress (muscular fatigue, psychological pressure, breathing equipment, etc.), 3) venous gas emboli associated with decompression, 4) Inflammation related to oxidative stress and microparticles. We present the results of a saturation divers monitoring campaign performed in the North Sea Danish sector, on the Tyra field, during 2022. The study was supported by TotalEnergies, the field operator, and performed by Boskalis Subsea Services, the diving contractor, onboard the diving support vessel Boka Atlantis. The objective was twofold: document the level of diving stress during saturation operations in the Danish sector, and compare the performances of two saturation procedures, the Boskalis and the NORSOK procedures.*

Materials and methods: *Fourteen divers volunteered for the study. The monitoring package include weight and temperature measurements, psychomotor tests (objective evaluation) and questionnaires (subjective evaluation), Doppler bubble detection and bioimpedance. The results were presented in a radar diagram that provides a general view of the situation.*

Results: *The data were analysed along 3 dimensions: work and environmental, desaturation bubbles, oxidative stress and inflammation. The results showed little or no variations from the reference values. No bubbles were detected after excursion dives and the final decompression, except for two divers with a grade 1 after arriving at surface. No statistical difference could be found between the Boskalis and the NORSOK saturation procedures.*

Conclusions: *At a depth of 40–50 msw corresponding to the Danish sector, the two saturation procedures monitored induce no or little stress to the divers. The divers know how to manage their diet, equilibrate their hydration and pace their effort. Data available on divers' post saturation period show a recovery over the 24–48 hours following the end of the decompression. Further research should focus on diving deeper than 100 msw where a greater stress can be anticipated.*

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Keywords: saturation diving, health monitoring, diving procedures validation, bioimpedance, bubble detection, environmental stress, working stress, decompression

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INTRODUCTION

Saturation diving with heliox (a gas mixture of helium and oxygen) is a standard method of intervention of commercial diving for offshore operations.

When saturation diving started in the North Sea during the 70's, the concern was decompression sickness (DCS). Fifty years later, saturation procedures have much improved and DCS has become a rare event. In Norway, the Norwegian Petroleum Safety Authority has been publishing saturation safety records since 1990. The site accessed on 21/09/2023 indicates only one DCS recorded since 2000. The corresponding DCS incidence cannot to be evaluated because the exposures are expressed as men hours in saturation and not saturation dives [1].

Because DCS incidence can no longer be used as safety marker, the monitoring of divers for other physiological and biological endpoints has become an alternative for evaluating the health and safety performances of a given saturation procedure.

Current saturation procedures are companies' proprietary procedures developed from historical sources such as the US Navy diving manual and adapted by experience (contractor procedures). Some countries have regulated the diving activities to the point where saturation procedures are specified for use in their offshore sector (national procedures). Norway for instance has published national procedures in the NORSOK standards that are influential in all Scandinavian sectors, including Denmark [2] [cited 2023 Sept 21].

To evaluate these saturation procedures, divers have been monitored through subjective evaluations [3], haematological changes [4], salivary bio marker [5], flow mediated dilation [6] or oxidative stress [7] during saturation. These studies have permitted identifying several stressors contributing to a general diving stress that can be described along three axes:

- The environmental (long confinement, heat/cold, dense gases) and the work (muscular fatigue, psychological pressure, breathing resistance, immersion, etc.).
- The level of vascular gas emboli (VGE) produced during decompression. Although there is no clear relation between the number of VGE measured and the risk of DCS, it is recognized that the smaller the number of VGE detected, the safer is the decompression [8–10]. The number of VGE [11] is still considered as a measurement of the decompression stress [12, 13].
- Several biological processes associated to inflammation recently identified in the literature [14, 15]. It has been shown that bubbles detaching from the endothelium create microparticles [16–18]. These microparticles trigger defence mechanisms such as platelets and neutrophil activation [19, 20], whilst elevated oxygen partial pressure increase reactive oxygen species (ROS), oxidative stress. All combine to produce vascular function impairment and inflammation [18, 21, 22].

Planning the monitoring of the diving stress requires to identify the pertinent stressors, source the specific monitoring equipment, and adapt to the operational constraints. For this purpose, we have developed a monitoring package based on our previous experience with an emphasis on multifrequency bioimpedance analysis (BIA) that provides a non-invasive way of indirectly evaluating inflammation.

We present the results of a monitoring campaign of saturation operations performed in the North Sea Danish sector. The objectives were to:

- document the level of diving stress during saturation operations in the Danish sector;
- compare the health and safety performances of two saturation procedures, the Boskalis procedures (contractor) and the NORSOK procedures (national).

MATERIALS AND METHODS

WORKSITES

A saturation monitoring campaign was performed in the North Sea Danish sector, on the Tyra field, in 2022. The study was supported by TotalEnergies, the field operator, and performed by Boskalis Subsea Services (BSS), the diving contractor, onboard the diving support vessel Boka Atlantis.

The study run from August and September and three teams of divers were monitored that performed three complete saturations.

UNITS AND NOTATIONS

As we dealt with operations, we kept the units used offshore for consistency. Depths and chamber pressure are expressed in msw and partial pressures in mbar. Chamber gauge pressures in msw can be converted to relative pressures using 1 msw = 10.0381 kPa according to EN 13319.

Considering normal saturation operations, we opted for the term decompression sickness (DCS) instead of decompression illness (DCI).

SATURATION OPERATIONS

A classic saturation operation proceeds as follows (Fig. 1).

- The chambers are initially compressed to 10 msw in 10 minutes for a 20 minutes leaks check. Compression then proceeds to the storage depth at 1 msw/minute.
- The chamber PO_2 at storage depth is controlled at 400 mbar. The storage depth is selected from the working depth using the standard excursion tables (42 msw storage depth for 50 msw working depth in the Norwegian

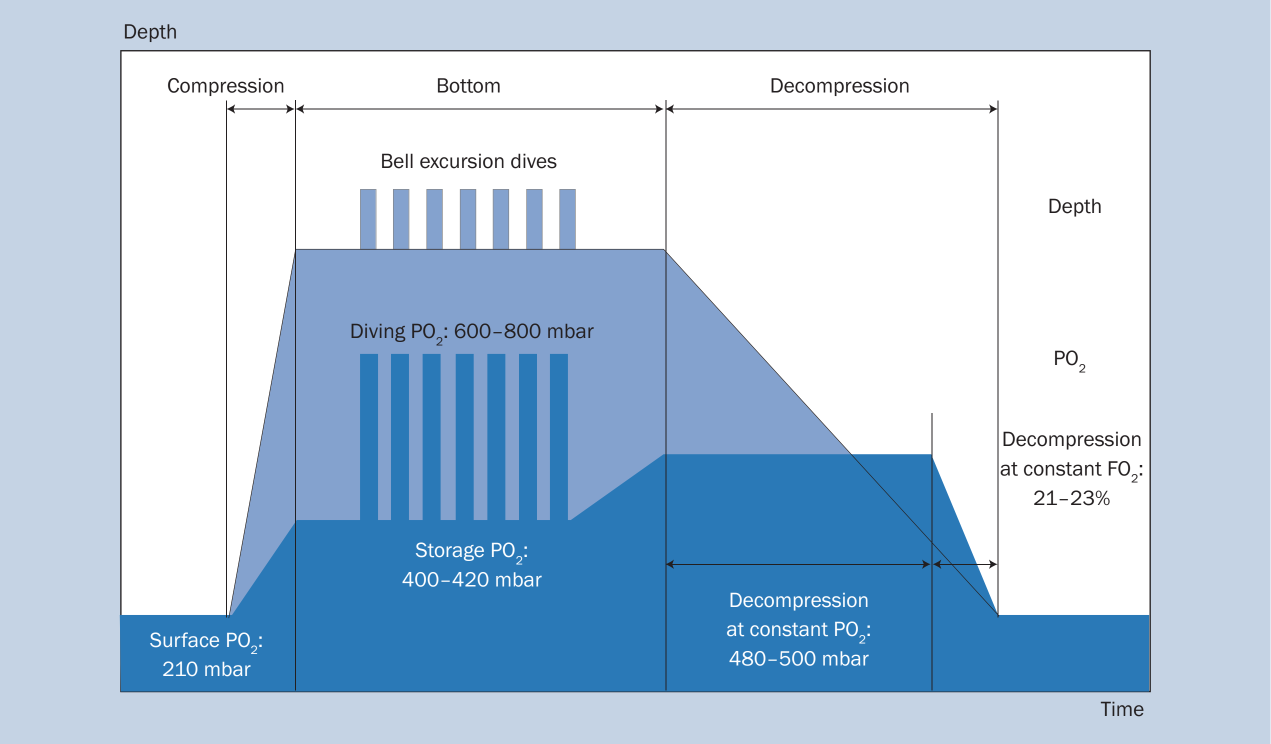

Figure 1. Description of BSS saturation procedures, depth profile (compression, storage depth, bell dives, decompression) and associated PO2 profile

sector, 41 msw storage depth for 50 msw working depth in the UK sector).

- During the bottom phase, divers perform one bell dive of 8 hours per day but may sometime skip a dive due to weather conditions or vessel transit. During the dives, the divers' breathing mixture is heliox with a PO$_2$ ranging from 600 to 800 mbar.
- Depending on the scope of work, the divers may have to change their storage depths by intermediate pressurization and decompression.
- The final decompression can only start after an 8 hours period following the last excursion dive, called the decompression hold.
- The decompression proceeds into two phases. It starts with constant chamber PO$_2$ (500 mbar in the UK, 480 mbar in Norway) until 15 msw and finishes with a chamber oxygen percentage maintained between 21–23% to limit the fire hazard.
- The saturation duration depends on the sector regulations. It is 14 days maximum bottom time in Norway and 28 days total saturation time in the UK.

SATURATION PROCEDURES

Two different saturation procedures were used during the monitoring project:

- the saturation procedures described in the Norwegian NORSOK U100 standards with an exemption for extending the saturation period to 28 days;
- the BSS saturation procedures described in their diving manuals (revision 2021).

The two saturation procedures specified similar storage depths for the project. There was only 1 msw difference between the excursion distances of the BSS procedures and the NORSOK procedures (Table 1).

The two saturation procedures also specified similar decompressions. There was only a difference of 4 h 30 between the decompression duration the BSS procedures and the NORSOK procedures at from 45 msw (Table 2).

SATURATION DIVES MONITORED

Saturation divers were organized into teams. The divers'

Table 1. Downward excursion procedures for the BSS and NORSOK saturation procedures

Procedures	Working depth	Storage depth	Excursion distance
BSS saturation	35 msw	27 msw	8 msw
NORSOK saturation	35 msw	28 msw	7 msw
BSS saturation	45 msw	36 msw	9 msw
NORSOK saturation	45 msw	37 msw	8 msw

Table 2. Final decompression for the BSS and NORSOK saturation procedures

	BSS procedures	NORSOK procedures
Decompression hold	8 hours	8 hours
Night stop	No night stop (Continuous decompression)	From 00:00 to 06:00
Chamber PO_2 Bottom to 15 msw	480 to 500 mbar	Used 480–500 mbar (Specified as 400–500 mbar)
Ascent rate (Expressed as distance in msw travelled per day)	60–30 msw: 24 msw/day 30–15 msw: 20.6 msw/day 15–0 msw: 16 msw/day	60–30 msw: 21.6 msw/day 30–15 msw: 18 msw/day 15–0 msw: 13.5 msw/day
Deco time from 45 msw (deco hold included)	2 days 15 hr 00 min	2 days 19 hr 30 min

teams were dispatched over two groups depending on the saturation procedure used (Table 3):

- the first group (Team 1 and 3) followed the BSS saturation procedures. Later called the BSS group;
- the second group (Team 2) followed the NORSOK saturation procedures for the decompression. Later called the NORSOK group.

Table 3. Saturations descriptions, using BSS or NORSOK procedures. Team 1, 2 and 3

Date	Event	Depth
02/08/22	Blow down (compression)	34 msw
23/08/22	Storage depth change	50 msw
24/08/22	Storage depth change	58 msw
25/08/22	Start final decompression	58 msw
28/08/22	End decompression	0 msw
First saturation, using BSS saturation procedures. Team 1, Divers 1 to 5.		
Date	**Event**	**Depth**
22/08/22	Blow down	34 msw
23/08/22	Storage depth change	50 msw
24/08/22	Storage depth change	58 msw
25/08/22	Storage depth change	58 msw
29/08/22	Storage depth change	48 msw
10/09/22	Start final decompression	37 msw
12/09/22	End decompression	0 msw
Second saturation, using NORSOK saturation procedures. Team 2, Divers 6–10.		
Date	**Event**	**Depth**
29/08/22	Blow down	37 msw
16/09/22	Storage depth change	34 msw
24/09/22	Start final decompression	34 msw
26/09/22	End decompression	0 msw
Third saturation, using BSS saturation procedures. Team 3, Divers 11 to 14.		

The divers of the two groups performed saturation at similar depths, doing the same bottom work, for the same duration. However, the various teams were involved in several storage depth adjustments. The tables below detail the profile of these saturations for the various team involved (Tables 3).

DIVERS' ELIGIBILITY AND ENROLMENT

The study subjects were volunteer, male, certified commercial saturation divers. They were declared fit for the saturation by the vessel hyperbaric nurse after a predive medical examination.

All experimental procedures were conducted in accordance with the Declaration of Helsinki [23] and were approved by the Academic Ethical Committee of Brussels (B200-2009-039). The methods and potential risks were explained in detail to the participants. Each subject gave written informed consent before participation.

A total of 14 divers accepted to participate to the study.

DIVERS' ANTHROPOMETRICS AND EXPERIENCE

As expected from saturation divers, all were very experienced divers with a long diving career (Table 4). (No statistical difference were found between the groups).

Saturation divers generally spend a lot of time maintaining a high level of physical fitness and are involved in all sorts of sports. Every diver in the group except one had a daily or at least weekly physical activity when at home (Table 5).

MONITORING PLAN

All the electrical devices complied with IMCA D041 recommendations for electronic devices used into a hyperbaric chamber. In particular, the equipment was locked-out to be recharged at surface (Table 6).

MONITORING SESSIONS

The monitoring sessions attempted to minimize interferences with operations. It was initially expected to have a bubble detection immediately after the return of the divers from

Table 4. Anthropometric parameters and professional experience of divers

Divers	BSS Group	NORSOK Group	All divers
Number	9	5	14
Age	50.5 ± 8.5	43.8 ± 10.7	48.2 ± 9.8
Height	1.80 ± 0.03 m	1.77 ± 0.03 m	1.79 ± 0.03 m
Weight	88.7 ± 7.5 kg	85.6 ± 5.5 kg	87.6 ± 7.0 kg
BMI	24.9 ± 8.1	27.6 ± 1.0	25.9 ± 6.7
Experience as commercial air diver	20.5 ± 8.2 years	12.4 ± 8.8 years	17.6 ± 9.3 years
Experience as saturation diver	23.7 ± 6.2 years	15.4 ± 16.4 years	20.7 ± 11.7 years

Table 5. Divers' physical activity when at home

Type of physical activity	All divers
Outdoor, intense like running, surfing, cycling, climbing, biking, kitesurf	73.3%
Outdoor, moderate like golf, hiking	6.6%
Indoor, intense: swimming, hockey, boxing, gym	20.0%
Moderate, or no sport	0%

Table 6. Monitoring plan measures and equipment

Stress	Selected measure and monitoring device
VGE levels after excursion dives and during/after the final decompression	Doppler bubble detection Azoth systems O'Dive Pro device
Psychomotor tests	PhysioPad application: reaction time, math calculation, time estimation, Flicker tests
Subjective psychological stress	PhysioPad application: Mood questionnaire
Subjective physiologic stress	PhysioPad application: Daily questionnaire
Oxidative stress, inflammation estimation	Bioimpedance analysis BiodyXpert 3 device
Nutrition	Weight measured by a scale
Thermal stress	Temperature measured by sub lingual thermometer

their bell dive but this proved unpractical. The protocol finally adopted allowed the divers sufficient time to clear equipment, take a shower and have dinner before they started their monitoring session. This corresponded to a delay of approximately 2 hours after returning from the bell dive (Table 7).

Three Monitoring Supervisors were successively onboard during the project to manage the data acquisition and avoid any additional task to the operational personnel.

DATA ACQUISITION: BUBBLE DETECTION

VGE level were measured by subclavian vein Doppler detection using the O'Dive PRO system designed by Azoth Systems (Ollioules, France) (Fig. 2). The system works inside a chamber and is designed to enable divers to make self-measurements. Visual feedback guides the operator for the correct positioning of the sensor. Following each measurement, an initial analysis is conducted to assess the signal quality. If the quality is inadequate, the operator is prompted to redo the measurement. The signals collected are then uploaded to a dedicated server where are processed and analysed.

A total of 772 recordings of right and left subclavian signals, i.e. 386 pairs of signals, were made by the 14 divers. After analysis, 93%, i.e. 720 recordings were found to be of a quality level that could be included in the analysis.

DATA ACQUISITION: PHYSIOPAD TESTS AND QUESTIONNAIRES

PhysioPad is a tablet-based application developed by the authors (JPI and CB) that can be used under pressure inside the chambers. PhysioPad provides several tests on

Table 7. Daily monitoring program

Phase	Time	Monitoring	Total duration
Pre-saturation	After the pre-saturation medical examination	Training to test package. Acquisition of reference values	1 hour
Bottom	Daily After shower and dinner	O'Dive bubbles detection Bioimpedance, Flicker, weight, temperature measures PhysioPad session	20 min per diver
Decompression	Daily After shower and dinner	O'Dive bubbles detection Bioimpedance, Flicker, weight, temperature measures PhysioPad session	20 min per diver
Post-saturation	Between 30 min and 60 min after the end of decompression	O'Dive detection Bioimpedance, Flicker, weight, temperature measures PhysioPad session	20 min per diver
	Between 4 hours and 6 hours after the end of decompression	O'Dive detection Bioimpedance, Flicker, weight, temperature measures PhysioPad session	20 min per diver
	Between 12 hours and 24 hours after the end of decompression	Bioimpedance, Flicker, weight, temperature measures PhysioPad session	15 min per diver

Figure 2. O'Dive Pro set

reaction time, mathematical calculations, time estimation, and cerebral arousal but also questionnaires (mood, daily questionnaire and post saturation):

- an objective evaluation of the subject's performances through four psychomotor tests;
- a subjective evaluation of the situation by the divers through questionnaires. Graphical sliding scales permit to quantify the answers.

DATA ACQUISITION

Weight was simply measured on a standard scale that was not electronic and could be compressed (Salter 145 BKDR, Germany). Body temperature was assessed as sublingual temperature for the estimation of the variations of the core temperature. Each diver was provided with his own disposable temperature devices.

Bio Impedance analysis: the BIA was based on the Biody X3 device designed by Aminogram (La Ciotat, France).

The device is a multifrequency impedance meter, accredited to the ISO 13485:2016 standard and CE marked, measuring impedance ranging from 1 to 1000 KHz. Conduction between the skin and the electrodes was standardized by wetting with a small amount of alcoholic gel (used for Covid protection). Data was transferred over Bluetooth to a tablet inside the chamber using a specific application (Fig. 3).

The results of the BIA tests were analysed using a program displaying the Cole-Cole diagram (Fig. 3) from which we derived two indexes.

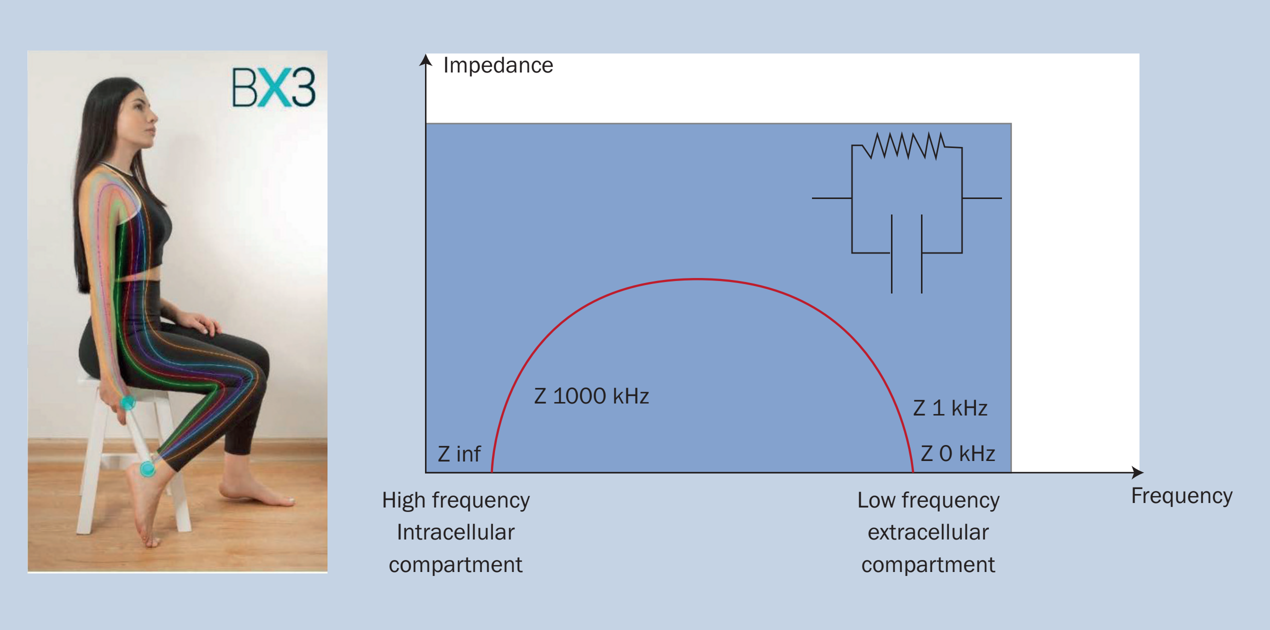

Figure 3. Use of the Biody X3 BIA device and Definition of the Impedance Ratio (IR) from the Cole-Cole diagram. The tissue is modelled as a simple high pass filter cell

The first index corresponds to the phase angle between the resistance and the capacitance of the impedance. It is measured at 50 KHz that corresponds to the maximum of the impedance. The phase angle is linked to the cell membrane that behave electrically as a capacitance because of its bi-layer structure. We assumed in our study that changes in the phase angle are caused by modifications to the membrane integrity and are directly related to the cellular oxidative stress.

The second angle corresponds to the impedance ratio (IR). The IR is derived from the Cole-Cole diagram using:

- the impedance value at the lowest frequency (in our case 1 KHz, also called Z1);
- the impedance value at the highest frequency (in our case 1000 KHz, also called Z1000).

And is defined as:

$$IR = 100 \times \frac{Z1}{Z1000}$$

This IR is related to the extracellular compartment via the Z1 value, and to the intracellular compartment via the Z1000 value. The ratio of Z1000/Z1 tracks the displacement of water between the intra and extra cellular compartments. We assumed in our study that changes in the IR index reflects the water movement related to a systemic inflammation (Fig. 3).

Note that during a saturation, the daily dives change the humidity of the skin and affect the contact impedance. Therefore, pre-saturation values obtained at surface in a dry environment could not be used as references for values measured afterwards during saturation. The reference value was therefore selected as the first day measurement inside the chamber.

STATISTICAL ANALYSIS

The normality of data was verified by means of Shapiro-Wilk or D'Agostino-Pearson tests.

When a Gaussian distribution was assumed, and when comparisons were limited to two samples, paired or non-paired t-test were applied. If the Gaussian distribution was not assumed, the analysis was performed by means of a non-parametric Mann-Whitney U test or, a Wilcoxon paired test. Taking the baseline measures as 100%, percentage changes were calculated for each diver, allowing for an appreciation of the magnitude of change rather than the absolute values. All statistical tests were performed using a standard computer statistical package, GraphPad Prism version 5.00 for Windows (GraphPad Software, San Diego, CA, USA).

The linear regression line was performed using the least squares method. A threshold of $p < 0.05$ was considered statistically significant, non-significant results are labelled NS. All data are presented as mean ± standard deviation (SD).

RESULTS

DATA COLLECTION

It appeared that after the end of the decompression, it was difficult to "catch" the divers at regular times due to operational constraints. Some subjects only performed one or two monitoring sessions of the 4 initially planned after the saturation.

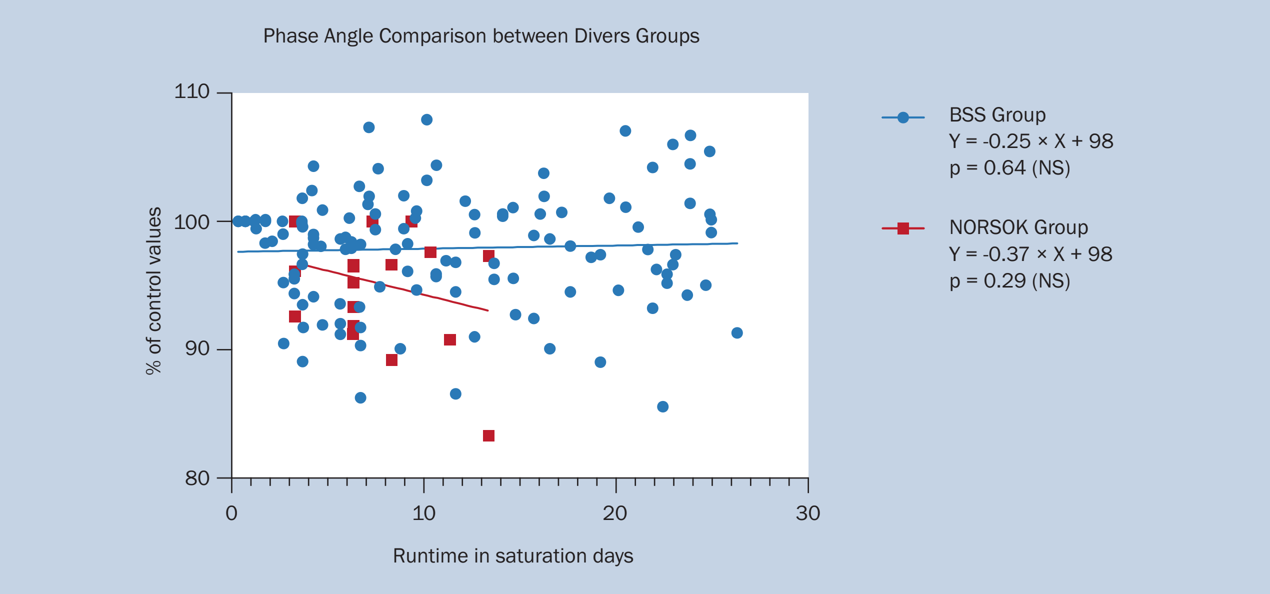

Figure 4. Evolution of the phase angle over the saturation runtime. The BSS diver group and the NORSOK diver group are compared

In any case, a total of 1280 tests/questionnaires results were collected under pressure and at surface, during 3 saturation dives.

COMPARISON OF THE BSS AND NORSOK SATURATION PROCEDURES

No significant statistical difference could be found between the BSS and the NORSOK saturation procedures in all the tests and questionnaires. An example is provided below that compares the evolution of the BIA phase angle over the saturation period, for the BSS and NORSOK diver groups (Fig. 4).

We first checked whether the slopes of the linear regressions were significantly different: for the BSS divers' group, the p value is p = 0.64. For the NORSOK divers' group, the p value is p = 0.29. Both BSS and NORSOK procedures are showing a non-significant variation of the phase angle over their saturation exposures.

We then checked whether the slope difference between the BSS and the NORSOK group was present. The slopes comparison gives a p value p = 0.26 showing no statistical difference. However, the elevations or intercepts of the regression line were showing a statistical difference with a p value = 0.0149 indicating that the divers of the two groups are different.

To explain this "discrepancy" we might consider a different health status of those participants, or a failure of the measuring system or other non-disclosed circumstances such as previous saturations, diving, inflammatory states conditions, etc.

Most of the other tests show no statistical difference.

We concluded that the data collected do not allow to consider that there is an advantage in using one saturation procedure rather than the other.

As the consequence, for the rest of the tests and questionnaires, the data from the BSS and NORSOK diver groups were merged for analysis and the conclusions refer to divers as a whole group.

PHYSIOPAD TESTS APPLIED TO ALL DIVERS

The PhysioPad package includes 4 tests: reaction time, time estimation, math calculation and Flicker test.

The results of the reaction time test and math test (Fig. 5) are consistent and remain steady over the saturation for all divers with a better performance for reaction time. We conclude that the divers' capacity to math calculation/ /reaction time was not negatively affected by either the depth neither the elapsed saturation time.

The results of the time estimation test show a steady state with no reduced performances of the divers (Y = –0.5441*X + 111.5, p = 0.21 (ns)). The results of the Flicker tests show a slight increase which also corresponds to improved performances of the divers (Fig. 6). Based on previous experiences, we attribute these improved performances to a learning curve and/or to the slightly higher level of oxygen in saturation that feeds higher brain performances [24–26].

PHYSIOPAD QUESTIONNAIRES FOR ALL DIVERS

The PhysioPad package includes 2 questionnaires: the mood and daily questionnaires.

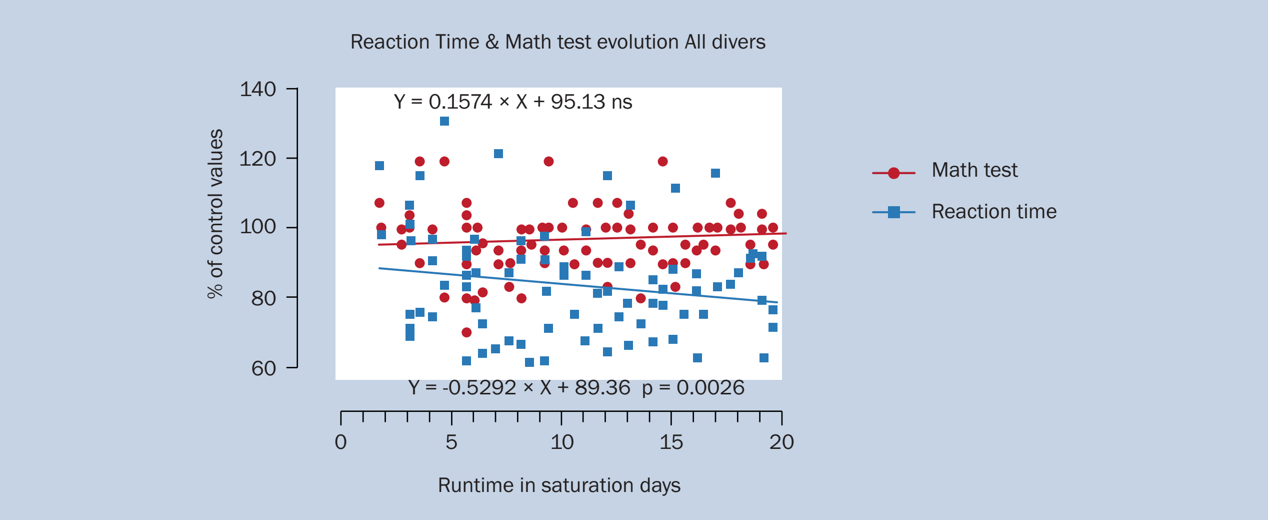

Figure 5. Reaction time test and Math test results evolution over the saturation time, for all divers

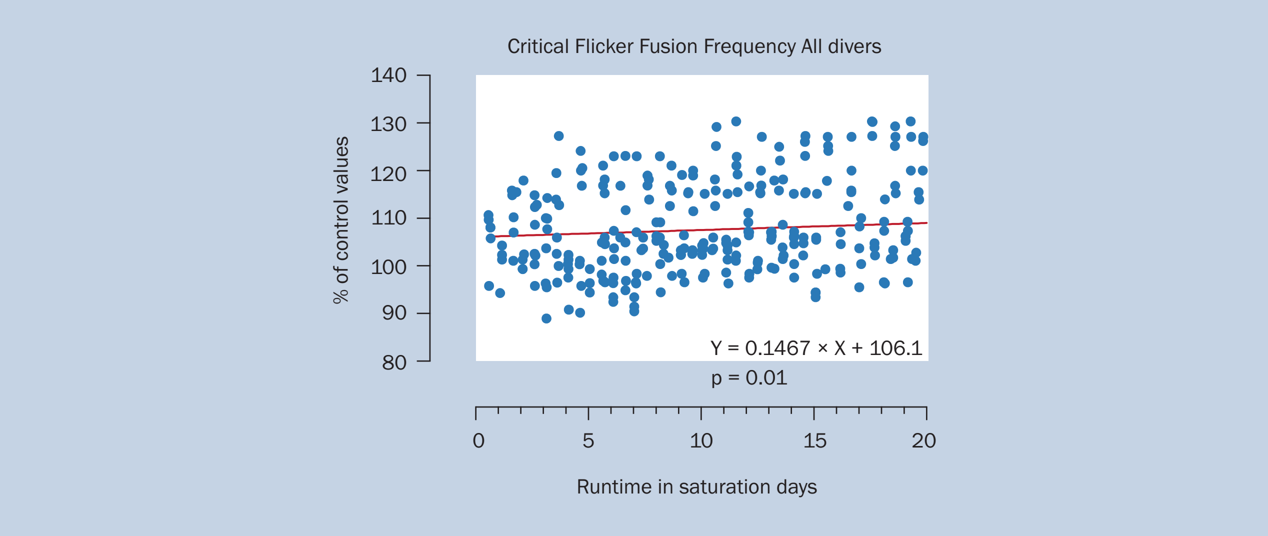

Figure 6. Critical flicker fusion frequency results evolution over the saturation time, for all divers

The analysis of the mood and daily questionnaire results showed no significant changes along the saturations for all divers.

We conclude that the saturation was considered as non-stressing and the divers felt at ease in what they would consider a routine saturation that that they can easily cope with.

BODY TEMPERATURE, ALL DIVERS

The central body temperature variations were estimated from the sub-lingual temperature variations.

No significant change could be measured in any diver during the course of the saturations.

We conclude that the chamber temperature control was adequate and the diving equipment (hot water suit) was well operated.

WEIGHT EVOLUTION, ALL DIVERS

Note that on some days, the vessel rolls prevented the use of scale.

The weight measurements presented no significant variations in any diver, during the course of the saturation. We conclude that:

— the divers well managed their food intake;
— their diet adequately covered their energy needs.

BUBBLE DETECTION, ALL DIVERS

The Doppler detection was conducted using the O'Dive Pro system:

— after bell dives;
— during the final decompression;
— after the end of the decompression.

The bubble signals collected during the 3 saturation exposures are shown in Table 8. Measures include two subclavian measurements that are combined into a single test. Bubble grades are defined according to the Spencer scale and expressed as G0 = bubble grade 0; G1 = bubble grade 1, etc.

The results indicated that no bubble was detected in the 13 divers during all the saturation and post-saturation period, except for **two divers who had a grade 1**, detected at surface, after final decompression.

We conclude that the bell excursion dives and the final decompression do not produce (or produce very few) bubbles.

BIA TESTS QUALITY SCREENING

The quality of the BIA tests collected were checked using an application displaying the Cole-Cole diagram for each measurement. We discovered this way that for unknown reasons, several of the NORSOK saturation diver tests came with a poor quality (incorrection position? defective device? skin resistance?) and had to be rejected.

Table 8. First saturation dive from Aug-2nd to Aug-28th, 2022 with BSS tables, Second saturation dive from Aug-28th to Sep--12th, 2022 with NORSOK tables, Third saturation dive from Aug-29th to Sep-26th, 2022 with BSS tables

Monitoring phase	Number of measures taken	Number of measures retained for analysis	Results
Saturation 1: BSS saturation procedures			
Storage at 34 msw	174	164	80 G0
Storage at 50 msw	6	6	3 G0
Storage at 58 msw	10	10	5 G0
Decompression	12	42	21 G0
Surface	46	46	23 G0
Saturation 2: NORSOK saturation procedures			
Storage at 50 msw	10	8	4 G0
Storage at 58 msw	10	8	3 G0
Storage at 48 msw	28	28	14 G0
Storage at 37 msw	116	112	55 G0
Decompression	18	17	8 G0
Surface	64	64	31 G0; 1 G1
Saturation 3: BSS saturation procedures			
Storage at 37 msw	136	124	59 G0
Storage at 34 msw	54	48	23 G0
Decompression	20	15	7 G0
Surface	38	28	13 G0; 1 G1

Despite the above-mentioned problems, 180 tests remained available for analysis after this screening.

BIA TEST: EVOLUTION OF THE PHASE ANGLE DURING SATURATION, ALL DIVERS

We associated variations of the phase angle to modifications of the cell membrane modification and oxidative stress.

The Figure 7 displays the evolution of the phase angle, for all the divers, over the bottom and decompression phase (excluding post-saturation period). The analysis of the slope variation of the phase angle over the entire saturation period is 0.016 (zero meaning horizontal). The p value is p = 0.49 which means that the slope is not significant.

We conclude that the phase angle, and therefore the cell membrane integrity, although in evolution, was not significantly affected during the course of their saturation.

BIA TEST: EVOLUTION OF THE IR INDEX DURING SATURATION, ALL DIVERS

We associated variations of the IR Index to tissue inflammation.

The Figure 8 below displays the evolution of the IR: for all the divers, over the bottom and decompression phase (excluding post-saturation period). The slope of the variation of the IR index, for all divers over the entire saturation period is 0.10. The p value is p = 0.35, which means that the slope is not significant. This slope can be considered as near zero.

We conclude that the IR index, for all the divers, was not significantly affected during the course of their saturation, and consequently, no significant systemic inflammation estimated by phase angle changes could be detected in all divers [27, 28].

BIA TEST: RECOVERY OF THE IR INDEX AFTER SATURATION, ALL DIVERS

We could collect BIA monitoring data after the end of the saturation for some divers who used the BSS procedures.

The Figure 9 displays the evolution of the IR index after the end of the saturation. It shows a rapid recovery is initiated in the next 2–3 days following the end of the decompression. In this figure, the fact that the percentage goes below the control values is understood as a positive coping reaction [27, 28].

The fast recovery of IR index is consistent with a similar recovery of the vascular function that we observed during the 12 hours following the end of the saturation in another study [6].

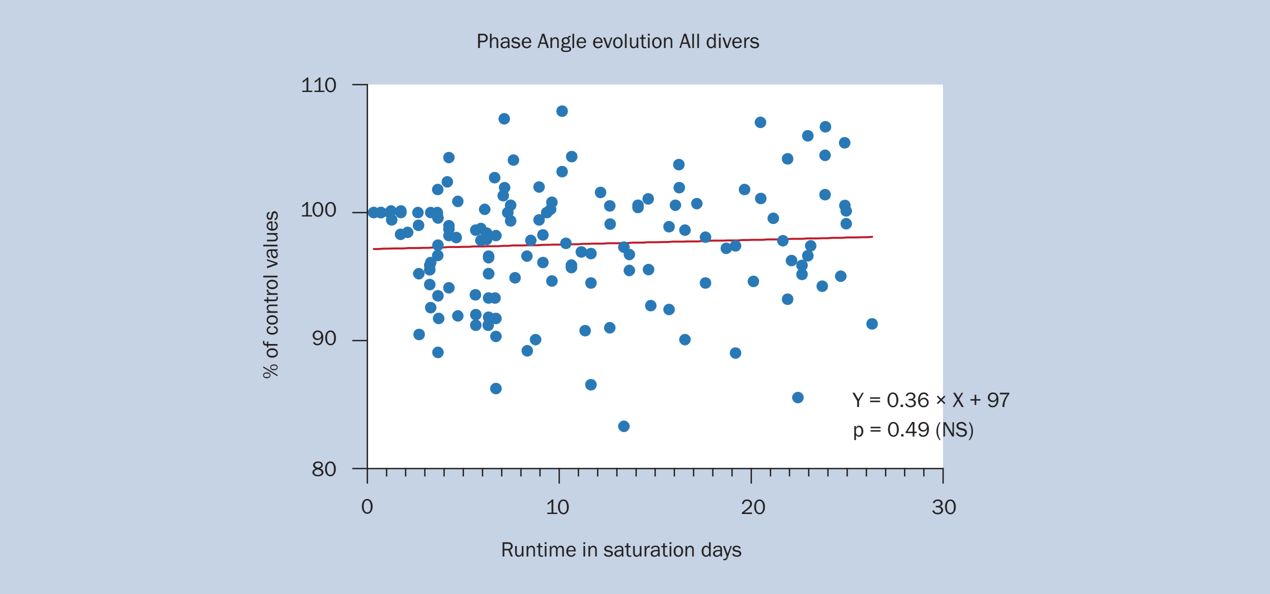

Figure 7. Phase angle measured by BIA, all divers, over bottom and decompression phases

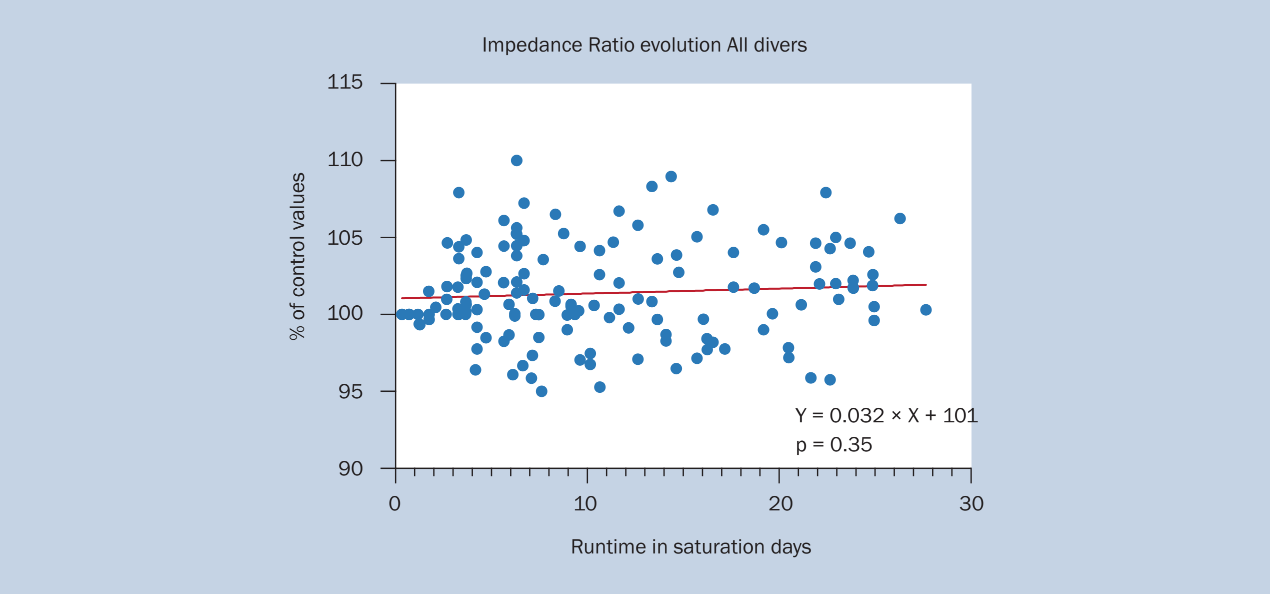

Figure 8. IR index computed after BIA, for all divers, over bottom and decompression phases

We conclude that for the divers monitored, a rapid recovery process was observed for the IR, and therefore, for the inflammation, which indicates that the divers well recovered from their saturation exposure.

DISCUSSION

EVALUATION OF THE DIVING STRESS IN THE RADAR DIAGRAM

We summarize the results of the study into a radar diagram which provides an instant visual representation of the divers' situation along the 10 stressors evaluated during the study (Fig. 10).

In this diagram; each measure is normalized using the following expression.

$$\textit{Radar value \%} = 100 \times \frac{\text{Measure value}}{\text{Control value}}$$

The colour coding is as follows. The border between the pale green and yellow sector corresponds to a 0% variation, which is the pre-saturation control value. The spread along the axis toward the red sector (critical) and the blue sector (optimum) is adjusted with an empirical scaling coefficient defined for each measure.

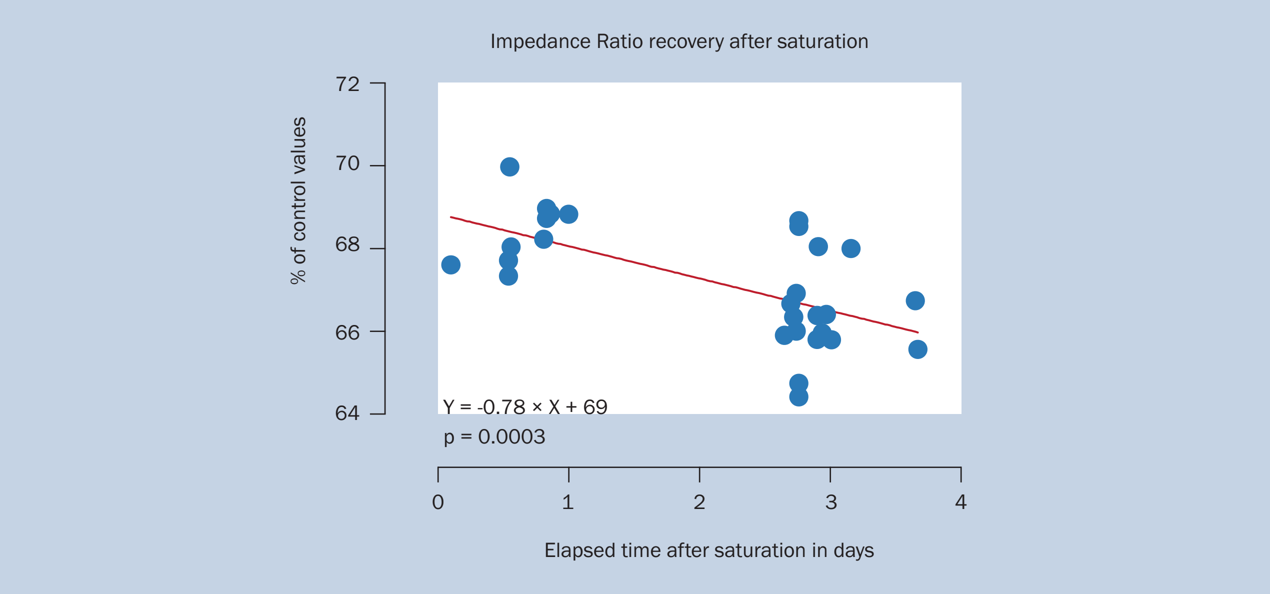

Figure 9. Post saturation recovery of the IR index

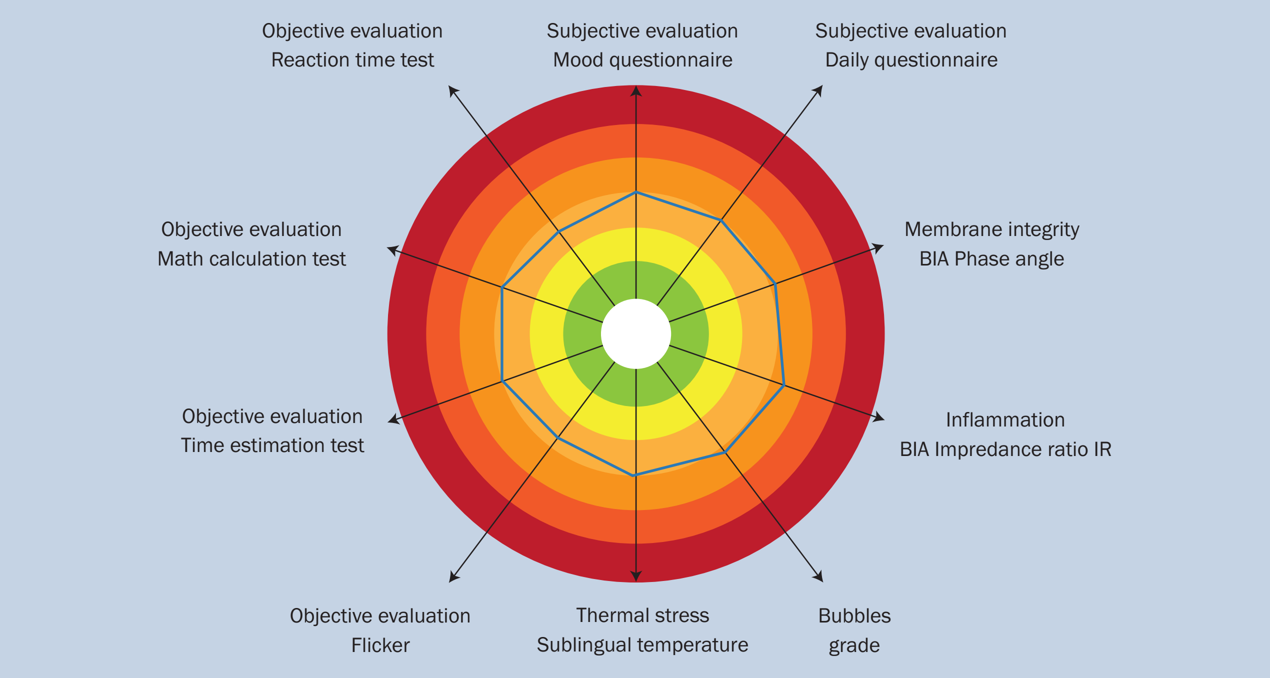

Figure 10. The radar diagram summarizing the study results along 10 axes, established for the 3 saturations, for all the divers, regardless of the saturation procedure used

Both the phase angle and the IR index did not display any significant changes over the saturation duration. They are consistent with the other measures performed with PhysioPad and Doppler bubble detection.

We conclude that:

- the stresses to which the divers were exposed during these 35–45 msw storage depth saturations were minimal and well compensated;
- more generally, Danish saturation operations correspond to a low level of saturation stress for the divers.

This study calls for the additional monitoring of saturation divers in deeper operations in the (120–150 msw) for comparison. This will allow to measure the range of the saturation stress over the North Sea full depth range.

COMPARISON OF BSS SATURATION AND NORSOK SATURATION PROCEDURES

According to the results of this monitoring project, there was no significant difference between the contractor procedures and the national procedures. In another words, our data do not allow to expect a benefit from using one saturation procedures instead of the other.

However, it is admitted that the study was limited by the fact that:

- the depth of the operations was shallow;
- the two saturation procedures are very similar at such depths;
- the number of divers involved in the study was small.

Hence, further research data must be collected to confirm the findings. Differences could appear between the two procedures at deeper depths.

POST SATURATION RECOVERY

The data collected on the IR index indicate a rapid recovery within 24–48 hours following the end of the final BSS decompression.

No measurements were available after saturation on divers using NORSOK procedures, but as the data suggest that the stress level is the same, the recovery rate should be the same as for the BSS procedures.

The fast recovery of the IR index suggests an adequate management of the dose and response of the organisms, which in turns indicate that the saturation procedures are associate with a moderate stress.

Further measurements are needed during deeper saturations.

CONCLUSIONS

Divers' monitoring was effectively conducted during actual saturation operations in the Danish sector, at a working depth around 34–58 msw. The monitoring plan was designed to analyse the saturation exposure along 10 different stressors and included multifrequency BIA analysis for the evaluation of the inflammatory stress.

The Doppler bubble detection performed after the excursion dives, during the decompression and after the saturation showed a very low level of circulating venous bubbles.

The BIA analysis of the test was performed using two indexes: the phase angle and the IR. The indexes did not display any significant evolution during the course of the three saturations.

This indicates that the saturation operations exposed the divers to a minimal stress to which the divers could cope without showing any alteration of their biological status.

Data available on divers' post saturation period show a recovery over the 24–48 hours following the end of the decompression. This means that the stress dose/recovery was easily managed by the divers.

No difference could be shown in this study between two candidate saturation procedures, the BSS procedures (contractor) and the NORSOK procedures (Norway).

Additional monitoring is required with divers exposed to greater depths to calibrate these potential effects in the full range of North Sea saturation operations.

ARTICLE INFORMATION AND DECLARATIONS

Data availability statement: The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Ethics statement: All experimental procedures were conducted in accordance with the Declaration of Helsinki [8] and were approved by the Academic Ethical Committee of Brussels (B200-2009-039).

Authors' contributions: All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication: Conceptualization: C.B, J.P.I., A.B., C.M. and S.S.; Investigation: H.P., JPI., S.S.,C.M., and A.B.; Formal analysis: C.B., A.L., H.R., A.B, P.B. F.V., H.P. and B.D.; Writing: J.P.I., C.B., S.S., C.M., H.P.,B.D., H.R., A.L. and P.B.; Review and editing: B.D., P.B., H.P., D.F., C.B., S.S. and J.P.I. Data curing: H.R., A.L., H.P., P.B., H.P., S.S., C.M. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest: A declaration of COI is included

Supplementary material: None

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