BALANCE TESTING AND DOPPLER MONITORING DURING HYPERBARIC EXPOSURE

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Abstract

Background: The effects of saturation diving to minor and medium depths on the postural system has not previously been adequately tested. The purpose of this study was to investigate if postural function is affected by a moderate hyperbaric exposure, and to see if a possible deterioration is correlated to the presence of intravascular bubbles. ***Hypothesis:*** Postural control and the vestibulo-ocular reflex are not affected during heliox saturation diving to 5 meters of seawater (msw). At greater depths, an effect may occur. ***Methods:*** Postural control was tested with the subjects standing on a static balance platform before, during, and after onshore experimental saturation chamber dives to 5 msw heliox, 20 msw air and to 100 msw heliox. Standard caloric testing with electronystagmography was performed before and after the heliox dives. Cardiac ultrasound and Doppler monitoring were used to detect possible venous gas emboli (VGE) during decompression in the heliox dives. ***Results:*** During the heliox exposure to 5 msw, no significant change in body sway was found. However, a significant change in body sway was found during an air dive to 20 msw and during the 100 msw heliox exposure. Caloric responses were unchanged immediately post-dive. After decompression from 5 msw, VGE were detected in three divers. During the 100 msw exposure, one case of VGE was observed. ***Conclusions:*** Exposure to hyperbaric heliox conditions corresponding to 5 msw, did not influence postural control significantly, while exposure to 100 msw heliox, and air diving to 20 msw, did. Although VGE were detected in the heliox dives, we could not find any correlation between this observation and postural instability.

Introduction[1]

The effects on the postural system of diving to minor depths have not previously been adequately tested. The cost-effectiveness of deep manned intervention relies on the efficacy and productivity of the divers in the water. Exact information concerning postural control during saturation diving may help in deciding when a saturation diver is best fit for performing tasks that require optimal coordination and balance.

Hyperbaric diving affects all parts of the human organism. The postural system may be influenced through multiple mechanisms during diving (7), e.g. caloric stimulation from cold seawater or from hot water in the suit, asymmetric middle ear pressure, inner ear barotrauma, decompression sickness, isobaric counterdiffusion, sensory deprivation, visual illusion, inert gas effects, breathing gas impurities and the High Pressure Neurological Syndrome (HPNS).

Computerized stabilometry based on input from a static balance platform offers an objective, simple, quantitative and reproducible method for measuring postural stability. It has been successfully used in pressure chambers under normobaric (13), hypobaric (11,15,16) and hyperbaric (1,2,6,14) conditions.

Stabilometry tests performed 20 years ago during a heliox chamber dive to a pressure corresponding to 485 msw, with a prototype platform, showed significant deterioration of postural stability (6). Since then, balance platforms have become commercially available and are in widespread use in otoneurology. In a simulated chamber air dive to 90 msw, this method demonstrated an increase in lateral and anteroposterior body sway with open and closed eyes (1). In another air dive to 90 msw, a deterioration in balance was observed sooner with increasing depth when the eyes were closed than with the eyes open (3).

Previous studies have shown transient vestibular imbalance as tested by caloric response with electronystagmography (ENG) in four of sixteen divers in connection with dives to 300-350 msw (12). It was concluded that this subclinical vestibular dysfunction had no practical impact on the divers' work. We have demonstrated in an earlier study that after exposure to a pressure corresponding to 450 – 470 msw there was a reduction in caloric response immediately post-dive as compared to pre-dive (14). In another 12 days onshore saturation dive to 450 msw, ENG monitoring was performed before, during, and after the dive. A decrease in the caloric induced nystagmus was seen in six out of eight divers upon reaching 450 msw, with total recovery on reaching the surface (17). In an air dive, ten divers were tested at 90 msw without detectable changes in the caloric VOR (2).

The objective of our study was to investigate changes in postural control during and after hyperbaric exposure, and whether caloric response was affected after simulated heliox saturation dives. Since experimental saturation dives are very expensive and require significant technical and personnel resources, experiments involving postural control had to be combined with other research activities during simulated saturation dives. The depth and dive profiles could accordingly not be dictated by our balance testing project. We had to adjust to the available time slots in a comprehensive research program.

Our hypothesis was that postural control and caloric response (vestibulo-ocular reflex - VOR) are not disturbed during heliox saturation diving to 5 msw, but when exposed to greater depths, an effect may occur.

Doppler monitoring was included in our study to detect possible venous gas emboli (VGE). When venous gas bubbles are detected, bubbles in arteries and other fluids

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and tissues may be present. Accordingly, the vestibular system (centrally and peripherally) could also be involved.

Material and methods

Three different depths were chosen as shown in **Fig. 1.** The first Series (Series A) was performed as two shore based, experimental heliox chamber saturation dives of 20 hours duration to 5 msw (150 kPa) at the facility of the Norwegian Underwater Intervention (NUI). During these simulated dives, two groups of four divers each breathed 21% oxygen, balance helium. The chamber was decompressed at a rate of 10 kPa/min to ambient pressure. The eight males participating in these simulated dives were aged 20-35 years (mean 23). Seven of them were experienced professional divers and one was a sports diver.

The second Series (B) included 29 male volunteer naval recruits (mean age 21 years, range 19-23) exposed to a pressure corresponding to a depth of 20 msw (300 kPa). This was a joint project between the Haukeland University Hospital and the Royal Norwegian Navy. The exposure lasted for 30 minutes and was performed with air as chamber and breathing gas, in the chamber facilities of the Royal Norwegian Navy at Haakonsvern Naval base. None of these subjects had previous diving experience.

The third Series (Series C) consisted of two simulated helium-oxygen dives (C1 and C2) to a maximum pressure corresponding to a depth of 111 msw (1.21 MPa). The pressure profile for both dives were similar and is illustrated in Fig 1C. Eight male subjects (mean age 34, range 21-41) participated in the first (C1). Eight males (mean age 37, range 28-44) participated in the second simulated dive (C2). Four of the subjects participated in both C1 and C2.

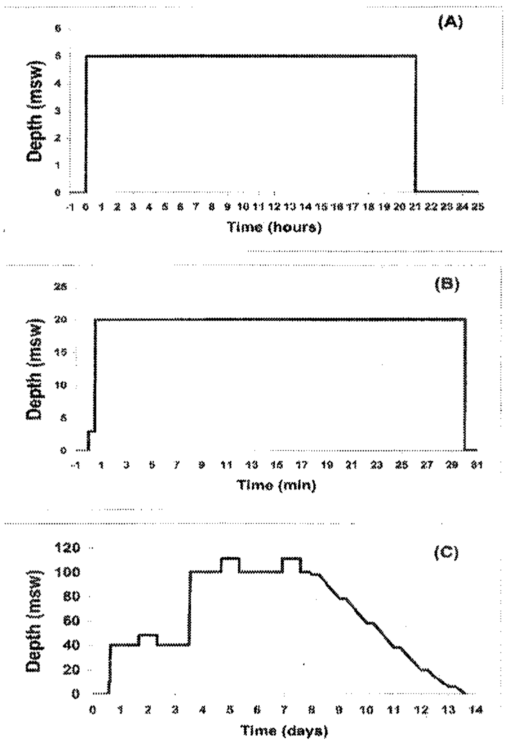

Fig. 1 The three different dive profiles.

NUI was overall responsible for organizing the heliox dives. Haukeland University Hospital, University of Bergen and Sintef Unimed also participated with independent scientific studies during these dives.

A pre- and post-dive standard clinical *ENT* (ear, nose and throat) *examination* was performed on all subjects by the same ENT specialist. It comprised inspection and palpation of the face and neck, inspection of the mouth and pharynx, anterior rhinoscopy, indirect laryngoscopy, nasopharyngoscopy and pneumo-otoscopy. In addition an *oto-neurological examination* was done before and after exposure for all the subjects participating in the heliox dives. This examination comprised a survey of the cranial nerve status and cerebellar function tests, in addition to the investigations of the present project.

Possible subjective *complaints of dizziness* were noted by a trained physician in the chamber, and each subject was observed and asked for possible unsteadiness during testing.

Computerized stabilometry (posturography) is used for measuring balance performance. It is non-invasive, causes no discomfort and is widely used for clinical investigations into disturbances of the postural system. The procedure is described in further detail elsewhere (13,14). In the present study the subjects were instructed to stand still on a static balance platform with their feet 7 cm apart and arms at their sides. Measurements were done for one minute with the eyes open (EO), looking at a small target at eye level two meters away, and for one minute with the eyes closed (EC). No training and only minimal instruction were needed. The tests were conducted under visually and acoustically standardized conditions in the hyperbaric chamber, once before and once after each dive, three times during the 5 msw exposures, twice at 20 msw and 17 times during 100 msw exposure.

A *balance platform* (Cosmogamma©, Via Zalloni, Bologna, Italy), measuring 40 x 40 cm, was used for data collection. The shift of the body's center of pressure (COP) at the soles of the feet during body sway was sensed by three mechanical-electrical transducers (strain gauges) in the platform. The signals were relayed by cable through a penetrator in the chamber wall to a computer (12 bit A/D resolution and 10 Hz sampling frequency) outside the chamber.

The *path length* the COP described during each one minute recording is determined by the effect of the gravitational force and the resulting isometric muscle contractions, and thus related to the effort of the balance system to maintain an upright posture. This parameter was used to evaluate the subjects' postural stability. In addition, the *mean speed* of the corrective movements in the anteroposterior and lateral planes were chosen to evaluate the postural stability in the two planes.

The *Romberg index* (RI) is the ratio between measured parameters with closed and open eyes. It was calculated for the path length and the anteroposterior and lateral speed of the COP. Usually, body sway will increase when closing the eyes, causing a detectable deterioration in performance. Accordingly, the RI will usually have a numerical value > 1.

Bithermal caloric testing according to Fitzgerald and Hallpike (10), was performed in each ear consecutively for all subjects participating in the heliox dives. The first test was conducted within 24 hrs before pressurizing, and then repeated within 24 hrs after surfacing. The system for recording and analyzing ENG-signals is developed in our laboratory. All data was analogously low pass filtered with an upper cut-off frequency of 30 Hz and a ten second time constant, before being digitized into a computer (12 bit A/D resolution and 100 Hz sampling frequency). The angular velocity of the slow nystagmus phase was computed and used as a measurement for the VOR.

Within subjects *analysis of variance* with repeated measures (RMA) was used to examine the various parameters describing the effect of the exposure on the postural system. When statistical significance was found ($p<0.05$), Tukey HSD (Honest Significant Difference) post hoc comparison was applied. For the caloric testing, the paired Student's t-test was applied.

Cardiac *ultrasound and Doppler* monitoring was used to detect possible venous gas emboli. The testing was done repeatedly during and for several hours after the hyperbaric exposure in all heliox chamber exposures. A Vingmed CFM 800 ultrasound color scanner (Vingmed sound, Horten, Norway) with either a 2.35 or a 4 MHz probe was used to visualize the pulmonary artery in a conventional B-scan. The same instrument produced a directed pulsed Doppler signal, which was interpreted acoustically. Finally, a continuous ultrasound doppler (Multi Dopplex II with a 2 MHz probe, Huntleigh health care, Cardiff, UK) was used according to the DCIEM/Kisman-Masurel protocol (8) for the detection of VGE.

The cardiac ultrasound signal was video taped. Initial interpretation of the Doppler signals (presence or absence of venous microemboli) was performed on-line by a trained scientist. The Doppler readings were scored according to the Kisman-Masurel protocol (8), with a score scale from 0 (no VGE) to IV (massive embolism). If VGE were detected, another trained observer, blinded to the initial score grading, evaluated the score postdive.

The project was approved by the Norwegian Regional Research Ethics Committee and informed consent was obtained from all subjects.

TABLE I. REPEATED MEASURES ANOVA WITHIN SUBJECTS EFFECT FOR THE 5 MSW DIVE (N=8).

		F(6,42)	P
Path length	(EO)	1.283	0.286
Path length	(EC)	1.562	0.182
RI	(EC/EO)	3.114	0.013*
Lateral speed	(EO)	0.107	0.995
Lateral speed	(EC)	2.090	0.075
RI	(EC/EO)	1.883	0.116
AntPost speed	(EO)	2.430	0.042*
AntPost speed	(EC)	1.204	0.323
RI	(EC/EO)	3.120	0.013*

EO: Eyes open, EC: Eyes closed, RI: Romberg index (ratio between measured parameters with closed and open eyes). P<0.05.

TABLE 2. REPEATED MEASURES ANOVA WITHIN SUBJECTS EFFECT FOR THE 20 MSW DIVE (N=29).

		F(3,84)	P
Path length	(EO)	5.202	0.002*
Path length	(EC)	8.422	< 0.0005*
RI	(EC/EO)	1.524	0.214
Lateral speed	(EO)	5.074	0.003*
Lateral speed	(EC)	4.565	0.005*
RI	(EC/EO)	0.538	0.657
AntPost speed	(EO)	4.833	0.004*
AntPost speed	(EC)	6.785	< 0.0005*
RI	(EC/EO)	1.323	0.272

EO: Eyes open, EC: Eyes closed, RI: Romberg index (ratio between measured parameters with closed and open eyes). * P<0.05.

Results

The clinical ENT and otoneurological examination did not disclose significant pathological findings pre- or post-dive. No subjective complaints of dizziness were noted during exposure in any of the dives.

For the 5 msw heliox exposure, the repeated RMA measures disclosed a significant increase in RI of the path length, for the anteroposterior speed with eyes open and for the RI of the anteroposterior speed (**Table I**). However when applying Tukey post hoc test, no significant level was reached.

Using RMA, significant change for various body sway parameters was also found for the air dive to 20 msw, as shown in **Table 2**. The relative increase in sway movements was similar for the EC and the EO conditions. Accordingly, RI did not change. The changes in sway parameters for movements both in the anteroposterior and lateral plane were significant. **Fig. 2** shows a marked increase in the path length for EO from the predive test to the first test at pressure, thereafter a decrease for the second recording at depth. Before surfacing the path length normalized. The post hoc Tukey test showed significant difference between the first in dive test and the post dive test in the EO condition for the path length ($p<0.019$) (Fig. 2a), lateral speed ($p<0.029$) (Fig. 2b) and for the anteroposterior speed ($p<0.033$) (Fig. 2c).

Table 3 and **Table 4** show the RMA for the two 100 msw heliox dives. Significant changes in body sway were found for several of the parameters such as the anteroposterior speed and for the lateral speed for the EC condition. When applying the post hoc Tukey test, most of the significant levels were found between the fourth recording at depth and later recordings.

The caloric vestibular tests for the heliox dives showed no significant change in the slow phase angular velocities between the pre- and post-dive tests, according to the paired Student's t-test.No one had values for side differences and directional preponderance outside our reference area (± 25 %) pre- or post-dive.

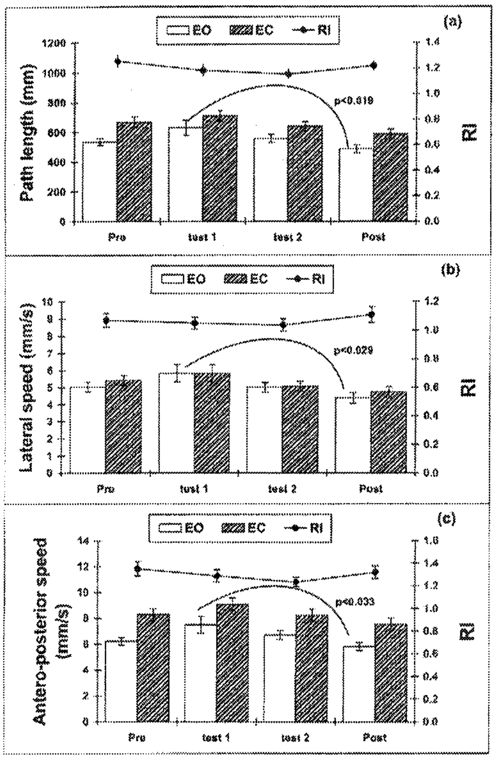

Fig. 2 Mean and standard error (SE) of path length (a), lateral speed (b) and anteroposterior speed (c) and the standard error for eyes open (EO), eyes closed (EC) with corresponding Romberg Indexes (RI) for the pre- and post exposure test and test 1 and 2 at a depth corresponding to 20 msw (n=29). Significant levels are indicated with curved lines and p-values.

After finished decompressions from dive A (5msw/150 kPa) (fig 1), two of eight divers had VGE with a maximum bubble grade of I in one diver and grade II in another. VGE was confirmed with ultrasound scanner in both (**Table 5**).

No VGE were observed at any time during C1.During C2, one single observation of Grade I VGE was done during an ascent from 48 to 40 msw.

Detailed results of the ultrasound and Doppler measurements will be presented elsewhere (Segadal K, Hope A, Risberg J, Thorsen E, Eftedal E, Koteng S, Brubakk AO. Venous gas emboli after decompression from shallow saturation dives, J Appl Physiol. In preparation).

TABLE 3. REPEATED MEASURES ANOVA WITHIN SUBJECTS EFFECT FOR THE FIRST OF THE TWO 100 MSW DIVE (C1) (N=8).

		F(18,126)	P
Path length	(EO)	1.364	0.161
Path length	(EC)	2.198	0.006*
RI	(EC/EO)	1.680	0.051
Lateral speed	(EO)	1.307	0.194
Lateral speed	(EC)	2.170	0.007*
RI	(EC/EO)	1.746	0.004*
AntPost speed	(EO)	1.850	0.026*
AntPost speed	(EC)	2.125	0.008*
RI	(EC/EO)	1.866	0.024*

EO: Eyes open, EC: Eyes closed, RI: Romberg index (ratio between measured parameters with closed and open eyes). * P<0.05.

TABLE 4. REPEATED MEASURES ANOVA WITHIN SUBJECTS EFFECT FOR THE SECOND OF THE TWO 100 MSW DIVE (C2) (N=8).

		F(18,126)	P
Path length	(EO)	1.447	0.121
Path length	(EC)	1.217	0.257
RI	(EC/EO)	1.491	0.104
Lateral speed	(EO)	1.287	0.207
Lateral speed	(EC)	0.738	0.767
RI	(EC/EO)	1.077	0.383
AntPost speed	(EO)	1.918	0.020*
AntPost speed	(EC)	2.074	0.010*
RI	(EC/EO)	1.844	0.027*

EO: Eyes open, EC: Eyes closed, RI: Romberg index (ratio between measured parameters with closed and open eyes). * P<0.05.

Discussion

The postural system is highly complex and includes feed back loops from several sensory modalities, e.g. superficial and deep tactile sense, proprioception from joints, tendons and muscles, vision and the vestibular system. Accordingly, major parts of the central nervous system are involved in the maintenance of balance.

Our earlier investigations have demonstrated that postural control becomes increasingly disturbed in heliox when the ambient pressure exceeds that corresponding to approximately 200 msw (2.1 MPa), but returns to normal when the ambient pressure is normalized (14). We found changes in postural control in all dives, but no significant levels were found when applying Tukey test for the shallow heliox dives to 5 msw. However, changes in the different sway parameters reached significant levels for both the air dive to 20 msw and the heliox dive to 100 msw.

TABLE 5. VGE AFTER SIMULATED HELIOX DIVE TO 5 MSW (N=8).

Time after finished dc	Bubble grade Rest	Bubble grade Movement
Subject #1		
25 min, 60 min	0	0
1h50min	I	II-
3 h 25 min, 4 h 40 min 5 h 40 min	0	0
Subject #2		
10 min, 60 min	0	0
1 h 25 min	0	I
2 h 0 min	0	II
3 h 20 min	II	III-
4h 35 min	I	II+
5h 40 min	0	II+
8h 40 min	0	0

We do not know why the air dives to 20 msw caused the quoted balance disturbances. Inert gas toxicity (nitrogen "narcosis") is known to affect the central nervous system, clinically presenting like alcohol intoxication. Cognitive functions, alertness and balance are among the functions being increasingly affected with air diving deeper than 30 msw (5). While psychometric tests have been commonly applied to assess nitrogen narcosis, scarce information is available concerning the postural effects (3). The unsteadiness observed at 20 msw calls for carefully controlled experiments discriminating between effects of hyperbaria per se vs. inert gas narcosis.

Postural control remained unchanged during isobaria at 100 msw, but deteriorated during decompression. Generally, loss of postural control can be a manifestation of inner ear decompression illness (DCI). Arness (4) reported vertigo/dizzness in 21/94 patients with DCI. The incidence of inner ear DCI is not known, and the distinction between CNS DCI, inner ear DCI and inner ear barotraumas represents a significant clinical challenge. Absence of VGE during saturation decompression from 100 msw in A1 and A2 does not support gas bubbles as a probable mechanism for vestibular dysfunction, although DCI may exceptionally occur even in the absence of VGE (18).

Inner ear barotrauma is a well recognised injury in divers (9). The slow decompression rate used in series A (8-16 msw/day) makes this diagnosis most unlikely. Further, none of the subjects complained of any ear discomfort. Minor lateral differences in middle ear pressure caused by different ability to equalize, can not be ruled out. However, clinically detectable alteranobaric vertigo (AV) has not been observed unless the pressure difference between the two middle ears exceeds 60 cm H_2O, which will cause a plugging sensation in one ear. That was not reported by our subjects. However, a subclinical form of AV, detectable only by a laboratory test like our posturography, can not be ruled out.

Hyperbaria at the present depths per se does not seem to affect sway, as all measured parameters of postural control remained unchanged at 100 msw. The small hyperoxia (40-50 kPa) introduced during decompression is yet another possible mechanism, but though no formal studies of postural control has been published during clinical hyperbaric oxygen therapy, vertigo and dizziness is not recognized as a common side effect of such treatment, in which patients are provided a hyperoxic breathing gas (typical pO2 240-280 kPa).

The concentrations of CO and volatile organic compounds were kept below administrative limits in the chamber atmosphere throughout the hyperbaric exposure. Accordingly, we do not think the observed postural instability could have been caused by pollution of the breathing atmosphere.

Since these were dry dives, we can exclude caloric stimulation as the cause of imbalance. The pressurization rates and maximum ambient pressures were also far too small to cause HPNS. For the same reason, no case of ear barotrauma occurred. There was no change of breathing gas mixture or ambient gas at depth, so isobaric counter diffusion can be ruled out.

Neither did the subjects show signs of fatigue, boredom or lack of mental concentration that could explain the observed instability. The mechanism underlying the observed minor change in body sway thus remains unknown.

We did not find a reduction in caloric response immediately post-dive as compared to pre-dive in the heliox dives, although we showed this in an earlier dive to 450 msw (14). We had no opportunity to do caloric testing during the dive or to do a follow up test later.

Conclusions

Exposure to hyperbaric heliox at pressures corresponding to 5 msw did not have a significant influence on postural control. Exposure to hyperbaric air to 20 msw and to a heliox pressure corresponding to 100 msw did influence postural control. VGE was detected in the heliox dives, but we could not find any correlation between this observation and postural instability.

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