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ORIGINAL RESEARCH

Balance Testing in Saturation Diving

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The literature is sparse and equivocal concerning the possible influence of hyperbaric exposure on postural control and the vestibular system. ***Hypothesis:*** Deep heliox diving may influence postural control and the vestibular system. ***Method:*** Multiple objective measurements of postural control were made in four divers by means of a static balance platform before, during and after an onshore experimental saturation heliox chamber dive of 32 d duration. Saturation pressure was 4.6 MPa, corresponding to a depth of 450 m of seawater (msw). Downward excursions to 470 msw were also performed. Clinical ENT and otoneurological examination, including bithermal caloric vestibular testing with electronystagmography (ENG) was performed before and after the dive. ***Results:*** Reduced postural control was detected by the balance platform test in all four divers from approximately 200 msw and deeper. Body sway showed a distinct increase during compression, reaching a maximum value during the bottom phase. The Romberg index was not suitable for describing shifts in postural stability. All sway parameters returned to pre-dive values after surfacing. Immediately post-dive, most caloric responses were reduced, compared to the pre-dive results. ***Conclusion:*** We conclude that deep heliox diving influences postural control and the vestibular system. Computerized stabilometry is a convenient and sensitive method of monitoring postural control during saturation diving. The path length of the center of pressure (COP) seems to be suitable as a monitoring parameter.

HYPERBARIC DIVING AFFECTS all parts of the human organism. The postural system may be influenced through multiple mechanisms during diving (8), such as 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 high pressure neurological syndrome (HPNS). The mechanism of HPNS is still poorly understood, and is being investigated (4).

The vestibular system plays an important role in maintaining postural control, especially in a neutrally buoyant diver in poor visibility. Many attempts have been made to examine the effects of hyperbaric exposure on the vestibular system both in man and in animals (11). The results are difficult to compare and seem equivocal.

A static balance platform offers a simple, quantitative and reproducible method of evaluating the postural system. Stabilometry tests performed during a heliox dive to 4.9 MPa with a prototype platform 20 yr ago (5) showed significant deterioration of standing steadiness. Since then, such equipment has become commercially available and is in widespread use in neurotology. The method has previously been used during a simulated chamber air-dive to 90 msw (1 MPa). An increase in lateral and sagittal body sway with open and closed eyes was detected (1). In another air-dive to 90 msw a deterioration in balance was shown to occur at a much faster rate with increasing depth when the eyes were closed than when they were open (3).

The objective of our study was to see if deep heliox diving impaired the postural system as measured by a static balance platform.

We also wanted to see if a deep saturation dive caused changes in the vestibulo-ocular reflex (VOR), detectable by standard caloric testing and ENG before and after the dive. Previous studies (11) have shown transient vestibular imbalance by ENG in 4 of 16 divers in connection with dives to 300–350 msw. It was concluded that this subclinical vestibular dysfunction had no practical effect on the divers' work.

In an onshore experimental saturation excursion chamber dive to 300 msw (3.1 MPa), caloric testing was performed on six participants who were breathing heliox at a pressure corresponding to 250 msw (11). The slow phase angular velocity of the caloric nystagmus signal showed a statistically significant reduction at pressure, as compared to pre- and post-dive registrations.

In another onshore deep dive to a maximum depth of 500 msw (5.1 MPa), reduced caloric response was detected in only two of the six participants who were breathing heliox at pressures corresponding to 400 and 500 msw, as compared to pre-dive values (11). There was no reduction in the caloric response post-dive, as compared to pre-dive registrations.

In a saturation deep diving experiment to 4.6 MPa for 12 d, ENG monitoring was performed on divers before, during, and after the dive. A decrease in the caloric-induced nystagmus was seen in six of eight divers upon reaching 4.6 MPa with total recovery on reaching the surface (13). In an air-dive study, 10 divers were tested at 90 msw without detectable changes in the caloric VOR response (2).

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The cost-effectiveness of deep manned intervention relies on the efficacy and productivity of the divers in 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.

MATERIAL AND METHODS

AURORA '93 was a shore based, experimental heliox chamber saturation excursion dive of 32 d duration, from April 18 to May 20, 1993 at the National Hyperbaric Centre in Aberdeen, Scotland. The saturation pressure was 4.6 MPa (46 ATA), corresponding to a depth of 450 msw, and excursions were limited to 20 msw downward. Accordingly, maximum dive depth was 470 msw. The dive had a compression phase of 2 d, and 2 isopression periods; 8 d at 450 msw and 4 d at 200 msw. The decompression lasted 18 d (7). The compression profile had been used before during a test dive (12), but was slightly modified. The scientific project was approved by the Grampian Health Board Ethical Committee.

All four subjects were commercial divers aged 28–42 (mean 33.5) yr with 9–22 (mean 12.75) yr of diving experience. Total previous saturation exposure was 80–800 (mean 320) d, and previous maximum depths ranged from 200–534 msw. Informed consent to attend the experiment was obtained from all divers predive, including their right to withdraw without prejudice to their interests at any time.

Computerized stabilometry used for documenting posturography is non-invasive and causes no discomfort. In our study the diver was standing with the feet 7 cm apart and the arms along the sides on a static balance platform, first for 1 min with the eyes open (fixed gaze) and then for 1 min with the eyes closed. No training and only minimal instruction was needed. The test was conducted under visually and acoustically standardized conditions in the same diving chamber, once before the dive, 16–17 times at pressure, and twice after surfacing. There were no practical or functional problems with the collection and processing of data before, during, or after the dive.

A balance platform (Cosmogamma©, Via Zalloni, 40066 Pieve di Cento, Bologna, Italy), measuring 40 × 40 × 8 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 hyperbaric chamber. A monitor screen provided on-line graphic and numerical presentations of different body sway characteristics, such as shift of the COP in the sagittal and frontal planes, and the path length the COP described during each 1 min registration. This ground projection of the COP is determined by the gravitational force and isometric muscular contractions, and thus related to the effort of the balance system for posture maintenance.

The Romberg index is the ratio between the path area (or speed) of the COP obtained with closed and open eyes. Usually, body sway will increase when closing the eyes, causing a detectable deterioration in performance. Accordingly, the Romberg index will usually have a numerical value > 1.

Various other sway parameters were also evaluated after the dive. Among these were the mean sway speed, maximum and mean sway amplitude and sway frequency in the sagittal and frontal planes, and time spent by the COP within circles with different diameters.

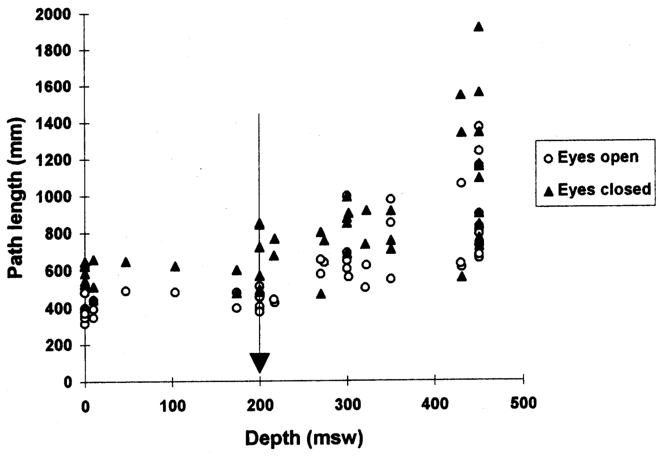

Fig. 1. Mean path length (in mm) for all four divers as a function of depth. The arrow indicates approximately at what depth an increase in the path length starts.

TABLE I. LINEAR REGRESSION BETWEEN THE DEPTH AND THE PATH LENGTH. THE "CRITICAL POINT" IS THE ESTIMATED VALUE WHERE THE PATH LENGTH STARTS TO INCREASE.

		Path length ≤ 200 msw			Path length > 200 msw			
Diver	Eyes Open/ Closed	n	p*	slope mm/msw	n	p*	slope mm/msw	Critical point msw
1	EO	9	0.418	0.28	11	0.003	2.64	211
	EC	9	0.420	−0.24	11	0.023	2.06	191
2	EO	9	0.020	0.81	10	0.001	0.98	†
	EC	9	0.030	0.75	10	0.256	1.15	†
3	EO	9	0.295	0.20	11	0.036	1.20	176
	EC	9	0.881	−0.03	11	0.028	1.21	189
4	EO	9	0.405	−0.27	11	0.012	1.53	213
	EC	9	0.130	0.79	11	0.078	2.32	215

The p values show if the slope is statistically different from a horizontal line.
* *t*-test; †The "critical point"-values for diver 2 is outside the meaningful range; EO: eyes open; EC: eyes closed; n: number of observations.

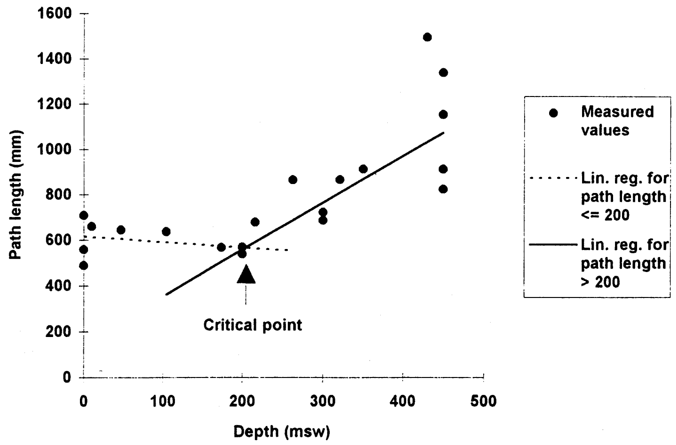

Fig. 2. Mean path length (in mm) as a function of depth for one of the divers. The arrow indicates at what depth ("the critical point") an increase in the path length starts.

The pre- and post-dive standard clinical ENT examination, performed by the same ENT specialist, comprised inspection and palpation of the face and neck, inspection of the mouth and pharynx, anterior rhinoscopy, indirect laryngoscopy, nasopharyngoscopy and otoscopy-pneumo-otoscopy.

The otoneurological examination comprised a survey of the cranial nerve status and cerebellar function tests. During electronystagmography (ENG), spontaneous nystagmus was looked for, and bithermal caloric testing was performed in each ear consecutively, modified after Fitzgerald and Hallpike (9) with 30-s water irrigation time. All data were analogously filtered with an upper cut-off frequency of 30 Hz and a 10-s 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 calculated by the computer and used as measurement for vestibulo-ocular response (VOR). (The system for registration and analyzing ENG-signals was developed in our laboratory).

In a modified step test the subject marched on the spot with high knee lifts for 1 min with the eyes closed, to see if there was deviation in any direction.

A general discomfort questionnaire with 20 questions, including questions on dizziness and unsteadiness, was filled in at regular intervals by each diver, 10 times before reaching 450 msw, and 9 times at 450 msw. The divers made tick marks on a visual analogous scale from 0 (no symptoms) to 10 (severe symptoms).

The Mann-Whitney U test, Student's *t*-test and linear regression analysis were used for the statistical calculations. To calculate at what depth the increase of the path length parameter started, a linear regression analysis was applied to the registrations deeper (>) and shallower (≤) than 200 msw. The regression coefficients describing the linear model shallower and deeper than 200 msw were used to find the intersection of the lines fitted to the two regions. The critical point (i.e., the intersection of the lines) was considered an estimate of the point where the increase in path length started.

RESULTS

A dominant trend of reduced postural control during compression in all four divers from approximately 200 msw and deeper seemed evident from visual inspection of the data plots (**Fig. 1**). This instability was reflected in different parameters characterizing the body sway, except in the Romberg index. Since the different parameters reflected the same postural stability change, we have chosen one of the parameters (the path length described by COP) for detailed analyses.

Table I gives the calculated critical point values of the path length for each diver. **Fig. 2** shows the intersection of the regression lines corresponding to the estimated critical point value for one of the divers. Of the divers, three had a critical point around 200 msw, while one had values outside a meaningful range due to a high grade of variation of the increasing path length values from approximately 200 msw and deeper.

To evaluate if the differences in the slope of the change in path length as a function of depth deeper (>) and shallower (≤) than 200 msw were statistically significant, the Mann-Whitney U test was applied. The results are summarized in **Table II,** and proved statistically significant for all cases.

The post-dive registration of the path length obtained within the first hour and about 40 h after surfacing with the eyes open and closed was quite similar to the pre-dive results in all four divers (**Fig. 3**). This figure also illustrates the increased postural instability at the bottom, both with open and closed eyes.

In **Fig. 4** the path length and the dive profile is shown as a function of consecutive registrations for all four divers. It clearly demonstrates increased instability with

TABLE II. STATISTICAL CALCULATIONS OF THE PATH LENGTH DEEPER AND SHALLOWER THAN 200 MSW.

Diver	Eyes Open/ Closed	Path length ≤ 200 msw			Path length > 200 msw			p-value*
		n	Mean	SD	n	Mean	SD	
1	EO	9	429	80	11	923	287	0.0001
	EC	9	596	68	11	949	268	<0.00005
2	EO	9	439	95	10	578	95	0.0076
	EC	9	683	93	10	1051	248	0.0001
3	EO	9	353	44	11	621	162	0.0004
	EC	9	452	39	11	634	159	0.0023
4	EO	9	508	76	11	750	182	0.0004
	EC	9	651	128	11	1070	361	0.0008

* Mann-Whitney U test; SD: Standard Deviation; n: number of observations.

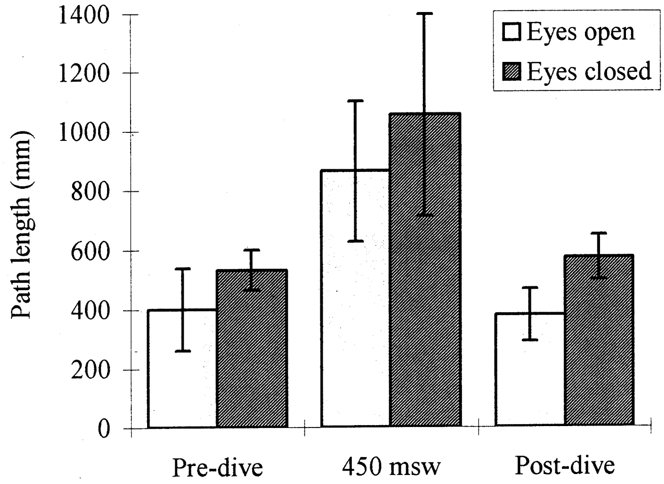

Fig. 3. Path length (mean values and SD) for the four divers before (eyes open: 400 ± 139, closed: 532 ± 67) and after (eyes open: 380 ± 88, closed: 575 ± 74) the dive, and at 450 msw (eyes open: 865 ± 236, closed: 1056 ± 342).

depth in all subjects, and normalization during decompression.

The Romberg index showed no statistically significant change during the dive, since the path area and speed increased almost equally with both closed and open eyes.

Other body sway parameters (e.g., oscillation amplitude and frequency) in the frontal and the sagittal planes also increased abruptly in all four subjects when reaching a pressure of approximately 2.1 MPa, corresponding to a depth of around 200 msw. A maximum was reached when arriving at the bottom. The predominant direction of the divers' body sway was in the sagittal (anterior-posterior) plane.

No classical signs of HPNS were clinically evident until reaching 450 msw. After reaching 300 msw and while staying at the bottom, all subjects reported slight dizziness and unsteadiness. On a scale from 0–10 in the questionnaire, all registrations ranged from 0–1, except that one diver reported a value of 2 once. At 450 msw, three divers had postural and intentional tremor. The diver with the most marked tremor also experienced irritability and one night even had auditory hallucinations. This was considered to be due to a combination of HPNS and sleep loss (6).

The clinical ENT and otoneurological examination did not disclose significant pathological findings pre-dive. One diver had a slight deviation to the left in his pre-dive step test, but post-dive the result was normal. There was no spontaneous nystagmus in any of the divers by clinical examination or detectable by ENG.

Post-dive, rhinitis and slightly dilated vessels in the tympanic membranes were noted in one of the divers. He had also had a slight nasal discharge during the dive. Two divers had slight external otitis post-dive, and one also had a slight deviation forward during the post-dive step test. Two divers had a transient high frequency hearing loss on audiometry shortly after reaching surface pressure (6).

The results from the caloric vestibular tests are given in **Table III** and **Fig. 5.** The angular velocities were significantly reduced from pre- to post-dive, according to Student's *t*-test ($p < 0.026$).

Calculated values for side differences (SD) and directional preponderance (DP) are given in Table III. One subject had an SD outside our reference area (±25%) pre-dive, but not post-dive. Another diver had a DP outside our reference area (±30%) pre-dive, but not post-dive. Only one diver had both SD and DP values outside our reference area post-dive.

DISCUSSION

The postural system is highly complex and includes feedback loops from several sensory qualities (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 (CNS) are involved in the maintenance of balance.

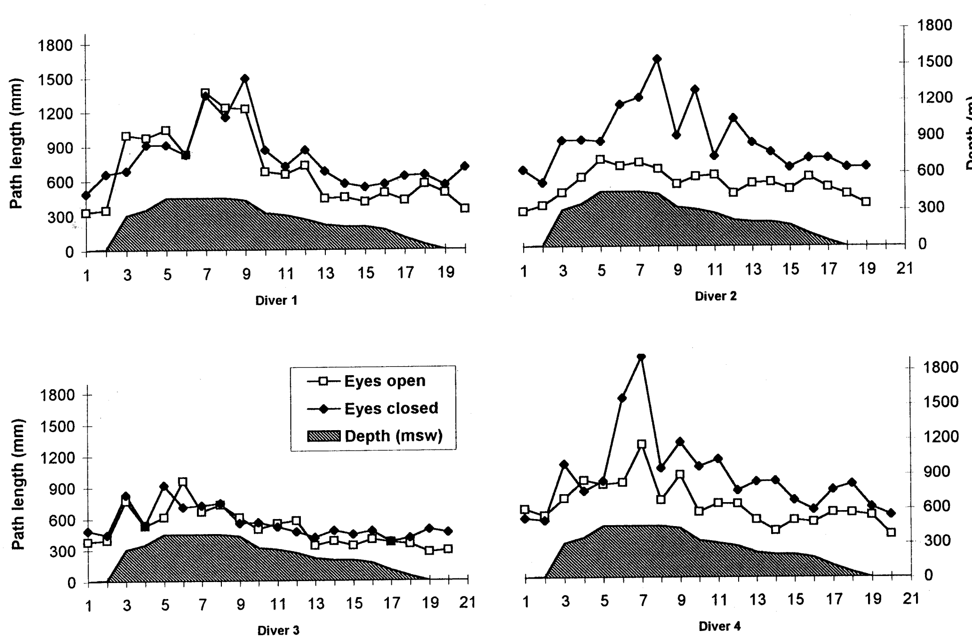

Fig. 4. The path length and dive profile as a function of consecutive registrations.

TABLE III. CALORIC VESTIBULO-OCULAR RESPONSE (VOR) PRE- AND POST-DIVE. THE NUMBERS ARE SLOW PHASE ANGULAR VELOCITIES (°/s).

Diver No.	1			2			3			4		
Stimulus	Pre	Post	Dif	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff
Left 30°C	30	34	4	17	14	−3	25	11	−14	7	6	−1
Right 30°C	20	8	−12	15	16	1	11	6	−5	20	11	−9
Left 44°C	44	21	−23	8	13	5	21	11	−10	18	4	−14
Right 44°C	27	21	−6	18	7	−11	14	8	−6	12	5	−7
SD	−22	−31	9	14	−8	22	−30	−22	−8	12	23	−11
DP	−6	31	−37	21	−16	37	10	6	4	−33	−15	−18

SD: side difference; DP: directional preponderance (positive values indicate right directed predominance, negative values indicate left directed predominance).

The vestibular system plays a central role in maintaining postural control, especially when vision, proprioception and tactile sense give little useful information, as in diving. The vestibular nuclei in the brain stem are the central part of this system, which have two-way connections with the peripheral vestibular organs in the inner ears, the motor nuclei of the eye muscles, cerebellum (mainly lobus flocculo-nodularis of archicerebellum), the spinal tracts, the reticular substance and the temporal cortex.

The sensitivity to HPNS is individual, but most of the deep divers we have contacted seem to agree that "something" becomes different when reaching a pressure corresponding to approximately 200 msw during compression, somewhat dependent on the rate of compression. For 10 yr, Norway has set the limit between ordinary routine commercial diving and deep diving at approximately 180 msw, based on the compression time needed to unite a deep and a shallow dive team for evacuation in a common hyperbaric life-boat. It was therefore interesting to note that the intersection-point of the stabilometry curves of three of the divers in the present investigation was around 200 msw.

Although our present investigation demonstrated that the postural control became increasingly disturbed in heliox when the ambient pressure exceeded approximately 2.1 MPa, it returned to normal when the ambient pressure normalized. This is in contrast with the effects of other CNS-active agents (e.g., alcohol) which can induce measurable after-effects.

The reduction in caloric response immediately post-dive as compared to pre-dive was consistent in all subjects. This differs from our posturographic results, which normalized immediately on reaching surface pressure. Other studies have shown a reduction in the caloric response while at increased ambient pressure, but not after surfacing (11). Unfortunately, we did caloric testing only once before, and once immediately after the dive. We had no opportunity to do caloric testing during the dive or do a follow-up test later. We are not yet able to decide the possible significance of this inconsistency between our two tests, but we will use any opportunity to expand our material. It would be interesting to repeat the caloric testing on future dives to determine if the postdive caloric depression occurs again, and if so, how long it takes to return to predive values.

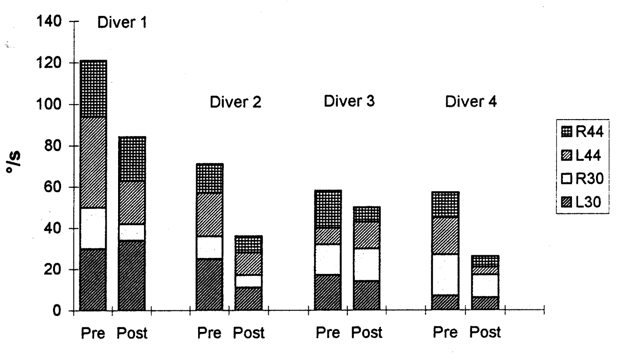

Fig. 5. This figure summarizes the four caloric reactions for each diver, before and after the dive. The Y-axis shows slow phase angular velocity in °/s (R44: right ear irrigation with water of 44°C, L44: left ear 44°C, R30: right ear 30°C, L30: left ear 30°C).

The signs of impairment of the balance system in these very experienced, meticulously selected and highly motivated divers was too small to affect their self-assessment of operational efficiency and well-being. General conclusions cannot be drawn from this limited material, but we think that if sufficient amount of practice or additional time for in-water work is provided, most experienced deep divers would in this respect probably be able to perform their tasks satisfactorily at depths corresponding to 4.6 MPa.

The increased postural instability from closing the eyes, as compared to keeping the eyes open, was not consistently greater during hyperbaric conditions than at surface pressure. Accordingly, the Romberg index did not change significantly during the dive. This is at variance with the results from an earlier air-dive (3), which showed an increased Romberg index at depth.

The detected disturbances of the balance system seem to correlate with the vestibular and motor signs of the HPNS. Arriving at 450 msw, three of the divers experienced intentional and postural tremor, while one diver had no tremor during the dive (10).

This investigation cannot decide which part of the postural system becomes affected. Any attempt to explain the mechanism behind the observed change in postural control would be mere conjecture. However, since the vestibulo-cerebellar part of the balance system plays a central role in the total regulation of postural control, one may speculate that this system could be a main site of disturbance.

CONCLUSIONS

Computerized stabilometry is a convenient method for monitoring the postural control during saturation diving.

It is more sensitive than clinical observation alone and provides objectively quantifiable data.

The path length of the COP seems to be a suitable parameter for the evaluation of postural stability during hyperbaric exposure. The path length increased distinctly in all divers from about 200 msw during compression, reaching a maximum during the bottom phase. During decompression, body sway decreased, reaching pre-dive values on surfacing.

The Romberg index was not a suitable parameter for describing postural control during this deep dive.

Post-dive, a reduction in caloric responses as compared to pre-dive values was found, but the possible clinical significance of this observation, which is at variance with the posturographic findings, is difficult to interpret.

Clinical otoneurological and ENT examination did not show changes of clinical significance post-dive as compared to pre-dive.

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