Simulated High Altitude Helium-Oxygen Diving

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BACKGROUND: Experience with commercial heliox diving at high altitude is limited. The purpose of this study was to evaluate the effects of acute high-altitude exposure on fitness to dive and the safety of decompression after heliox diving while using U.S. Navy heliox decompression tables with Cross correction.

METHOD: Four professional male divers were consecutively decompressed in a hypo- and hyperbaric chamber to altitudes of 3000 m (9842.5 ft), 4000 m (13,123.4 ft), and 5200 m (17,060.4 ft) during the 8-d study. The dive profiles tested were to 30 m (98.4 ft) for 60 min at all three altitudes and, in addition, a dive to 50 m (164 ft) for 60 min at 5200 m altitude. The decompression followed the U.S. Navy heliox decompression table. The safety of decompression was evaluated by precordial Doppler venous gas emboli (VGE) monitoring during the decompression stages and postdive monitoring of the divers for symptoms of decompression sickness (DCS). Effects of altitude exposure were measured as subjective rating and EEG signs of sleepiness and fatigue, clinical symptoms of high altitude disease, and fitness to dive.

RESULTS: A total of 24 person-dives were conducted. There were no VGE detected during the decompression and no postdive symptoms of decompression illness. Both the EEG findings and subjective evaluation indicated increased sleepiness and fatigue at 3000 m, 4000 m, and 5200 m, all compared with the sea level baseline. During the diving phase, both the EEG findings and subjective evaluation scores returned to the baseline and the divers successfully completed diving.

DISCUSSION: Diving at high altitude with a short acclimatization period appears safe despite divers exhibiting clinical symptoms and EEG signs of impairment by hypoxia at high altitude. Despite a small number of dives, the results of this study indicate that our application of U.S. Navy standard heliox decompression tables with Cross correction is effective and could be used for underwater constructions up to 5200 m altitude, with due caution.

KEYWORDS: high altitude, heliox diving, decompression, electroencephalography, subjective evaluation.

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Diving and underwater operations at high altitude are crucial for hydropower construction in China, with many sites exceeding an altitude of 5000 m (16,404.2 ft). Current diving practices are based on previous studies of air diving to depths of 30 to 50 m (98.4 to 164 ft) with combined in-water and surface decompression.[14]

However, the gas density of air at 50 m (164 ft), the cold, and the narcosis limit working capacity of divers, raising operational and safety concerns. Replacing heliox for air seems justified, but the decompression for heliox diving at this altitude has not been tested before. This study was designed to test the safety of diving and decompression with heliox at altitude using U.S. Navy heliox decompression tables with Cross correction.

The study was conducted in cooperation with Shanghai Jiao Tong University, the Naval General Hospital, and Chiba University. Specific aims of this study were to address common symptoms caused by precipitous ascent to altitude that may affect fitness to dive and to test the decompression safety of U.S. Navy heliox decompression tables corrected with the Cross method.

Acute exposure to high altitude may result in acute mountain sickness (AMS). Most divers may have difficulty sleeping, which is associated with changes in the regulation of wakefulness and state of arousal. This is reflected in the electroencephalogram with increased slow wave activities and decreased alpha activities as measured with the Alpha Attenuation Test

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(AAT).[4,11] Previous studies have shown that changes in AAT which occur when divers fly directly from sea level to 5000 m (16,404.2 ft) altitude are completely reversed by increased oxygen partial pressure while diving.

Among the issues involved with high-altitude diving, adjustment of decompression schedule is the most critical. However, most approved decompression procedures have been developed for sea level conditions and cannot be applied directly to diving at altitude. For diving at an altitude of 300 m (1000 ft) or higher, the U.S. Navy diving decompression tables must be corrected.

The Cross Correction is a simple rule for the correction of standard air decompression tables for altitude diving and is described in the U.S. Navy Manual.[3] However, very few formal reports about actual diving at altitude using this method are available and, especially, there are no documented dives using Cross correction with U.S. Navy heliox diving tables.

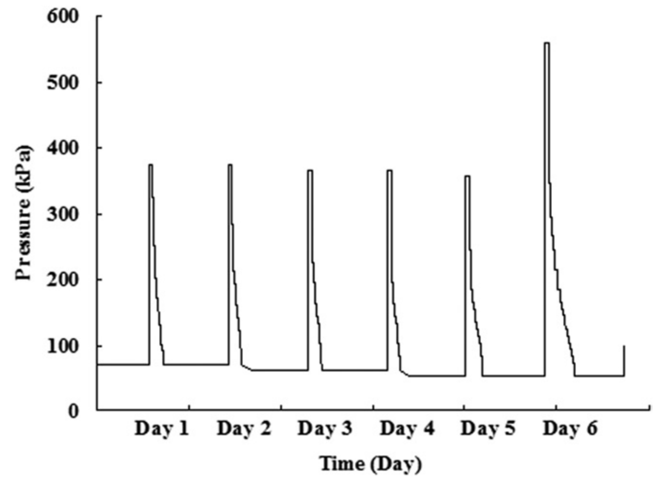

Fig. 1. The diving profiles and decompression schedules. We completed the 3000 m/30 m diving on days 1 and 2, 4000 m/30 m on days 3 and 4, 5200 m/30 m on day 5, and 5200 m/50 m on the last day. The hypoxia tests were implemented from 08:00 to 12:00 at 3000 m, 4000 m, and 5200 m, respectively, and the diving tests were implemented at 13:30 on the same day. The divers returned to the diving altitude after diving.

METHODS

Subjects

The subjects in the study were four male professional divers 26 to 45 yr old and with a body mass index of 21 to 25.4. Their dive experience varied from 2 to 27 yr of diving at depths of 18 to 60 m (5.9 to 196.9 ft) and none had a history of decompression illness. They underwent regular strict medical examinations and psychological training, a hypoxia test at 3000 m (9842.5 ft) altitude, and an oxygen sensitivity test at 3 ATA.

The divers were asked to refrain from hard exercise, drinking caffeinated beverages, and smoking tobacco 24 h before and during the whole study period. All subjects were carefully informed about the nature of the study, the hazards involved, and their right to withdraw from the study at any time without prejudice or penalty. The study protocol was approved in advance by the Human Ethics Committee and Institutional Review Board of the Institute of Underwater Technology, Shanghai Jiao Tong University. Each subject provided written informed consent before participating.

Equipment

The simulated dive was conducted in a two-compartment hypo-/hyperbaric chamber. The carbon dioxide partial pressure was maintained at less than 0.02%, and the oxygen concentration was maintained at 21% during the high-altitude exposure.

Procedure

Four high altitude dive profiles were tested. The dives were to 30 m (98.4 ft) for 60 min at altitudes of 3000 m (9842.5 ft), 4000 m (13,123.4 ft), and 5200 m (17,060.4 ft), and a dive to 50 m (164 ft) for 60 min at an altitude of 5200 m. The diving process arrangement is shown in **Fig. 1**.

The study started with a confinement of the divers in the hyperbaric chamber at sea level pressure for 48 h, during which time the baseline physiological testing was conducted. This was followed by three-step decompression to high altitude at a rate of 10 m $\cdot$ min^{-1} (32.8 ft $\cdot$ min^{-1}). At each of the three altitudes, the divers conducted one dive on each of 2 consecutive days. The first dive at 3000 m (9842.5 ft) altitude started 16 h after altitude was reached. Moving to the next higher altitude followed 2:45 h after the end of the second dive. After the last dive at an altitude of 5200 m (17,060.4 ft), divers stayed at altitude for 15:25 h before recompression to sea level. The recompression to sea level lasted 8.6 min. The total duration of the chamber ride from the beginning of decompression to the recompression back to sea level lasted 6 d and 16 h. Upon return to surface level, the divers were under medical observation for 24 h.

Decompression was planned using U.S. Navy decompression tables for heliox diving and corrected depths and decompression stops.[13] The atmospheric pressure and diving depth conversion at different high altitudes are shown in **Table I**. The conversion depth of decompression stations at different high altitudes are shown in **Table II**.

Compression from surface to dive depth was conducted at the rate of 6 to 8 m $\cdot$ min^{-1} (19.7 to 26.2 ft $\cdot$ min^{-1}) to avoid possible equalization problems while using compressed air. All dives were conducted breathing heliox via mask with 40% oxygen for the 30-m (98.4-ft) dives, 26.7% oxygen for the 50-m (164-ft) dive, and decompression until 16 m (52.5 ft). Divers were breathing oxygen via mask, with scheduled air breaks. During the dive, the divers pedaled a bicycle ergometer at 60 rpm for 5 min with a load of 0.5 kg. The temperature in the hypobaric chamber during surface intervals was ~24–26°C. During a compression to a simulated dive depth the temperature reached up to 35°C for a short time before it was brought back to ~24–26°C by the ventilation and air conditioning system. The theoretical depths for a 30-m dive at 3000 (9842.5 ft), 4000 (13,123.4 ft), and 5200 m (17,060.4 ft) were 43.4, 49.3, and 57.8 m (142.4, 161.7, and 189.6 ft) and the total decompression

Table I. The Atmospheric Pressure and Diving Depth Conversion at Different High Altitudes.

	ATMOSPHERIC PRESSURE			EQUIVALENT SEA LEVEL DEPTH (m)	
HIGH ALTITUDE (m)	kPa	mmHg	ATA	30	50
0	101.33	760.00	1	30	50
3000	70.10	525.77	0.69	43.36	72.27
4000	61.63	462.24	0.61	49.33	82.21
5200	52.58	394.40	0.52	57.81	96.35

times were 165, 171, and 243 min, respectively. The theoretical depth for the 50-m dive at 5200 was 96.4 m (316.3 ft) and the total decompression time was 474 min.

Precordial bubble detection was performed with a continuous-wave Doppler apparatus (DUG, Sodelec, Marseille, France), equipped with a 5-MHz probe and piezoelectric crystal area of 3 × 6 mm. The divers were trained to position the probe precordially and acquire the signal while resting in the left decubital position. The quality of the signal was monitored in real time by an expert rater outside of the chamber and taped for later evaluation. Monitoring was conducted at every other decompression stop for 1 min during the last minute of the stop and it was also conducted when the divers "surfaced" after diving. The recorded signals were graded according to the Spencer Doppler code on a scale from 0 to 4.[12]

The divers were observed for 24 h after the dive for symptoms of decompression sickness. They were asked to report any health changes in comparison to their pre-experiment health status.

The subjective level of daytime sleepiness and fatigue during sea level, high altitude, and diving was assessed using a Visual Analog Scale (VAS).[5] It is a measurement instrument for subjective characteristics or attitudes that cannot be directly measured. The scale consists of a 10-cm long line for sleepiness and fatigue, respectively, with each line having bipolar end anchors (representing ~0–10 scores from left to right) related to sleepiness and fatigue, and is completed with minimal time and effort. When responding to a VAS item, subjects specify their level of agreement to a statement by indicating a position along the line conveying how they feel at that point.

Table II. Conversion Depth of Decompression Stations at Different High Altitudes.

	HIGH ALTITUDE AND CONVERSION STATION DEPTH (m)		
STATION AT SEA LEVEL (m)	3000	4000	5200
2	1.38	1.22	1.04
4	2.77	2.43	2.08
6	4.15	3.65	3.11
8	5.53	4.87	4.15
10	6.92	6.08	5.19
12	8.30	7.30	6.23
14	9.69	8.51	7.27
16	11.07	9.73	8.30
18	12.45	10.95	9.34
20	13.84	12.16	10.38
25	17.30	15.21	12.97
30	20.75	18.25	15.57
35	24.21	21.29	18.16
40	27.67	24.33	20.76
45	31.13	27.37	23.35
50	34.59	30.41	25.95
55	38.05	33.45	28.54
60	41.51	36.49	31.14
65	44.97	39.53	33.73
70	48.43	42.57	36.33

The objective arousal level was measured with the AAT. A resting EEG was recorded for 1 min with the eyes open and 1 min with the eyes closed, repeated three times. The tests were conducted during confinement at sea level, at altitude before the dive, and at the maximum depth of the dive. The alpha attenuation coefficient (AAC) of the EEG was used as an index of central nervous system activity. AAC is calculated by dividing the α-wave power during closed-eyes by the α-wave power during open-eyes. AAC rises when the arousal level rises, and falls when the arousal level falls.

EEGs were fast Fourier transformed for each 5.12 s of data, not including artifacts such as ocular movement. EEG activity was recorded with Ag/AgCl electrodes affixed with electrode paste on the midline parietal (Pz), central (Cz), and frontal (Fz) electrode sites using the international 10-20 system.[7] Linked earlobes were used as a reference with a forehead ground. A bipolar electro-oculograph (EOG) was recorded with electrodes placed above and below the left eye. It was used for amplification with a time constant of 0.3 s and an upper cutoff frequency of 30 Hz. The sampling frequency was set at 250 Hz. The EEG was amplified by appropriate devices (Biopac Systems, Goleta, CA).

Statistical Analysis

All data were reported using mean (± SE). The influence on EEGs and subjective evaluation of high altitude and diving were analyzed using a one-way repeated measures ANOVA. In addition, the LSD method was used to provide a post hoc test. The data for each high altitude and high altitude diving exposure were analyzed and compared using the paired sample *t*-test. The level of significance was set at $P < 0.05$.

RESULTS

The four divers carried out a total of 24 person-dives testing four dive profiles at three different altitudes. The diving profiles and decompression schedules are shown in Fig. 1.

None of the divers had any equalization problems during the compression stage. The Doppler detection of venous gas emboli (VGE) showed the absence of bubbles at decompression stops in all divers. No post-dive symptoms of decompression sickness (DCS) were reported or observed.

All divers showed mild acute mountain sickness to some extent at 3000 m (9842.5 ft), 4000 m (13,123.4 ft), and 5200 m (17,060.4 ft) simulated high altitude environments with symptoms including headache, dizziness, anorexia, and dyssomnia. Diver 2 had a headache as a chief complaint at all altitudes and a fever at 5200 m altitude. However, both the headache and the fever disappeared after simulated diving. Diver 3 showed an elevation of blood pressure which returned to normal after simulated diving. Diver 4 felt numbness in the fingers except the thumbs in both hands. Symptoms improved after diving and the independent diving medicine expert decided it was mild enough and did not require intervention. At 2 wk after the study, the diver was symptom free. All divers had diminished appetite and poor nocturnal sleep at the different altitudes. After diving, sleep quality improved and appetite increased in all divers. No DCS occurred during the process of decompression or after decompression.

Changes of AAC at the altitudes of 3000 m (9842.5 ft), 4000 m (13,123.4 ft), and 5200 m (17,060.4 ft) in comparison to the baseline at sea level [$F(3,28) = 6.501$, $P = 0.012$] and during diving to 30 m (98.4 ft) at high altitudes [$F(2,17) = 0.434$, $P = 0.667$] are shown respectively. The AAC at 3000 m was not different than at sea level. The AAC at the altitude of 5200 m was significantly decreased compared to the AAC at sea level ($P = 0.025$) and to the AAC at 3000 m ($P = 0.012$). The AAC during diving operations to 30 m was not different from the AAC at altitude of 3000 m and 4000 m, but it was increased in comparison to the AAC at 5200 m ($t = -9.724$, df = 3, $P = 0.002$). The comparison of AAC at 3000 m, 4000 m, and 5200 m, and during diving to 30 m at respective elevations are shown in **Fig. 2**.

Scores of the subjective evaluations of sleepiness showed an increase with altitude in comparison to sea level in **Fig. 3** [$F(3,28) = 8.254$, $P = 0.006$], which was significant at 4000 m ($P = 0.046$) and 5200 m ($P = 0.046$). Scores for subjective evaluation of fatigue significantly increased at every altitude in comparison to sea level [$F(3,28) = 9.522$, $P = 0.004$], which was significant at 3000 m ($P = 0.029$), 4000 m ($P = 0.015$), and 5200 m ($P = 0.033$), as shown in **Fig. 4**.

These results indicate that at high altitude the human arousal level of the brain decreased while sleepiness and fatigue increased. During hyperbaric exposure, the AAC and subjective evaluation returned to the baseline values.

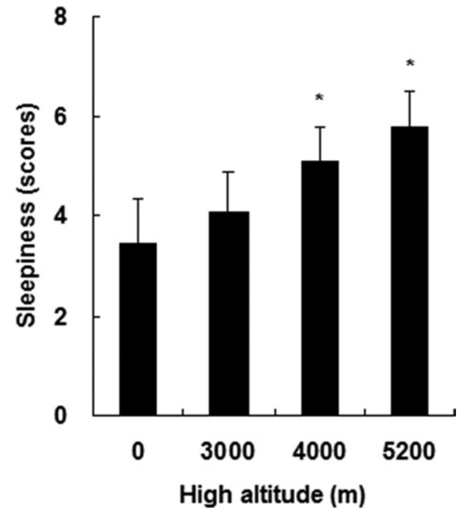

Fig. 3. The sleepiness score of different altitudes. *$P < 0.05$ vs. 0 m. Error bars are SEM.

DISCUSSION

Upon arrival at the altitude of 3000 m (9842.5 ft) above sea level, the divers all suffered from an acute altitude reaction to hypoxia. The 16-h stay before the dive was intended to assure reduction of nitrogen in the blood, but it was not long enough for acclimatization. The dive, which started 16 h after arrival to an altitude of 3000 m, may have prevented more serious symptoms and enhanced acclimatization similar to the practice of "stay high-sleep low." Subsequent altitudes followed after a 20-h postdive period while acclimatization was still in process. Upon successive ascents to the altitudes of 4000 m (13,123.4 ft) and 5200 m (17,060.4 ft) the divers again suffered symptoms of headache, dizziness, anorexia, and dyskoimesis related to

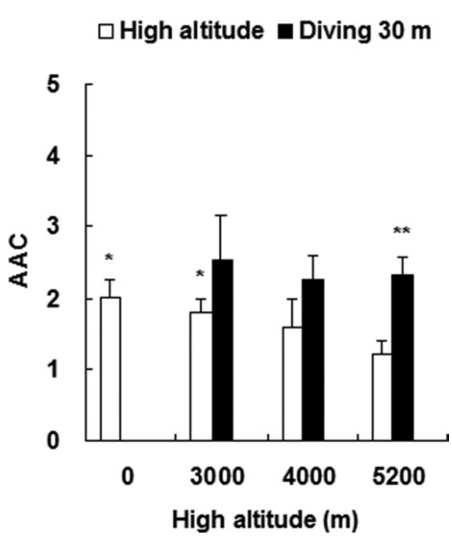

Fig. 2. The AAC of different altitudes and diving (D) groups at Cz. *$P < 0.05$ vs. 5200 m high altitude; ** $P < 0.01$ vs. 5200 m high altitude. Error bars are SEM.

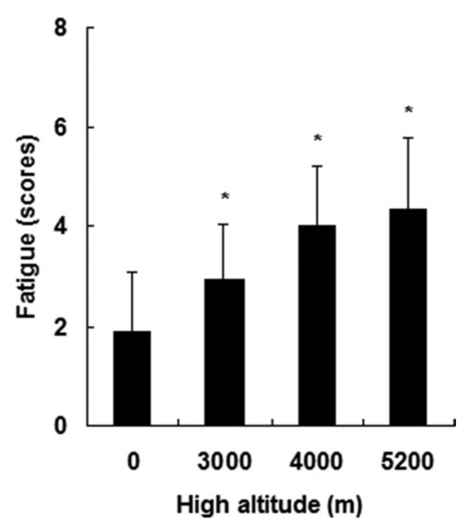

Fig. 4. The fatigue score of different altitudes. *$P < 0.05$ vs. 0 m. Error bars are SEM.

hypoxemia, which was documented by oximetry and published previously.[6] The most severely affected diver could only lie in bed. However, when the exposure to hypobaric hypoxia was replaced by exposure to hyperoxia during the dive, the above-mentioned symptoms quickly disappeared and the divers were able to operate normally.

In this investigation, EEGs at Fz, Cz, and Pz were measured and AAC before and after high altitudes and diving exposure were analyzed. The effects of the high altitude exposure on AAC at Fz were significant. The AAC decreased significantly at altitude in comparison to the baseline. The decrease was progressively greater with the increasing altitude. As an index of the arousal level of the cortex, the AAC's findings indicated that brain activity was reduced under hypobaric hypoxic conditions. During diving exposure, the AAC at Pz were greater than that at the surface at high altitude. The AAC almost reached the sea level control values. Accordingly, it can be concluded that the hyperbaric hyperoxic exposure reverted the hypobaric hypoxic effects and increased the cortical arousal levels. Fatigue and sleepiness were also improved.

Separate tables for diving at altitude have been calculated by various authors, but the tables themselves were not sufficiently tested. The Buhlman tables for diving altitude were calculated based on 106 simulated hyperbaric chamber dives with participation of five divers starting from 3000 ft (914.4 m) altitude. Two dive profiles were tested: 30 m (98.4 ft) for 50 min and 50 m (164 ft) for 20 min. In addition, 143 subjects conducted 278 controlled open water dives at altitudes between 900 and 1700 m (2952.8 to 5577.4 ft). These data were used to calculate air diving decompression tables for altitudes from 0 to 3200 m (0 to 10,498.7 ft) above sea level and for up to 70 m (229.7 ft) depth.[2] Since then, little information about use and effectiveness of this table has been available.

When a diver arrives at a high-altitude site, his tissues will hold an excess of dissolved nitrogen (super saturation). This residual nitrogen load has to be accounted for, as in a repetitive dive. Depending on altitude, this nitrogen surplus will call for a decompression obligation corresponding to an extension to the actual bottom time, similar to the situation for a repetitive dive. After 12 h staying at the new altitude, the diver's tissues are considered to be in equilibrium with the new ambient pressure and there is no penalty that must be observed for the first dive.

The Cross correction method was used for the U.S. Navy Standard Air decompression table and routine diving in Davis Lake, CA, at 6200 ft (1890 m) without decompression sickness.[1] It can be used to correct the U.S. Navy standard air decompression table for diving at altitudes up to 3000 m (9842.5 ft), and only for the short no-decompression stop dives. For dives with indicated mandatory decompression stops, the Cross coefficient was meant to be used for altitudes of 1900 m (6233.6 ft) or less only.

Jacques Cousteau did a series of exploratory dives at Lake Titicaca (3810 m/12,500 ft in altitude). Scientific dives in the Andes at 5928 m (19,448.8 ft) altitude to 9 m (29.5 ft) depth and in the Himalayas at 4785 and 5330 m (15,698.8 and 17,486.9 ft) above sea level, using oxygen for 22 dives and nitrox for 2 no-decompression shallow dives, have been conducted.[9] The Indian Navy conducted a limited number of no-decompression stop air dives at 2134 m (7001.3 ft) altitude and oxygen dives at an altitude of 4328 m (14,199.5 ft).[11] Scientific diving was conducted at 5913 m (19,399.6 ft) using a rebreather at depths up to 4.5 m (14.8 ft) for up to 25 min.[10]

Four air dives with bubble monitoring were conducted at Tilico Lake (4919 m/16,138.5 ft) to depths of 15 and 30 m (49.2 and 98.4 ft) using the Cross correction method. No decompression symptoms were reported, but one diver had a very high grade of VGE.[8] However, there are no reports of any diving similar to commercial diving operations involved with underwater construction work at high altitude and, especially, there is no experience with heliox diving at altitude.

In our study, decompression from heliox diving after equilibration at altitudes of up to 5200 m (17,060.4 ft) using the schedule developed by applying Cross correction to standard U.S. Navy heliox decompression tables appeared to be safe. The divers did not develop any symptom of DCS, and they did not exhibit VGE at decompression stops. The Cross correction method is very simple. While it does not take into account all the subtleties of saturation and desaturation, it may result in some additional conservatism. Cross correction does not account for lesser density of fresh water in comparison to sea water, which is an error that results in longer decompression. Cross correction also assumes that the diver starts the dive with the residual nitrogen saturated at sea level.[1] This may be critical when diving with compressed air and more complex correction methods were developed to correct this.[13] However, our divers followed the U.S. Navy recommendation, waiting at least 12 h after arrival at high altitude before performing the first dive. Thus, we used a simple ratio correction method as originally proposed by Cross. This may have resulted in a longer than necessary decompression schedule, but regarding the harsh environment of intended high altitude dive sites, we chose safety over efficacy. We also waited at least 2.5 h after the dive to ascend to the next higher altitude to avoid possible decompression sickness due to the residual helium from the preceding dive. This also allowed additional time for acclimatization and may have prevented more severe symptoms of hypobaric hypoxia.

Weaknesses of our study include having a small number of dives and unequal times of acclimatization at various altitudes. In cases where divers must travel to an altitude of 5200 m (17,060.4 ft) for a dive operation, they would still have to observe a reasonable ascent regimen to avoid serious high altitude disease. Alternatively, they could be partially acclimated in a hypobaric chamber at sea level before a flight to altitude using a protocol like the one used in our study. The decompression stops in this case were very long and some VGE could have occurred there. Monitoring during the decompression stops was mainly used to spot possible early occurrence of VGE and to correct decompression on the go if needed.

Diving at high altitude with a short acclimatization period appears safe despite divers exhibiting clinical symptoms and EEG signs of impairment by hypoxia at high altitude. Once exposed to hyperbaric hyperoxia, all symptoms were resolved, EEG findings returned back to normal, and divers regained their normal functional capabilities to conduct dives.

At the equivalent altitude of 3000 m (9842.5 ft), 4000 m (13,123.4 ft), and 5200 m (17,060.4 ft), 24 person-times of helium-oxygen dives were completed and scheduled tasks were accomplished. No VGE were detected during decompression stops and no signs or symptoms of DCS were noted after decompression back to the surface at altitude. Despite a small number of dives, the results of this study indicate that our application of U.S. Navy Standard heliox decompression tables with Cross correction is effective and could be used for underwater constructions diving up to 5200 m altitude, with due caution.

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