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ORIGINAL ARTICLE

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Changes in maximal performance of inspiratory and skeletal muscles during and after the 7.1-MPa *Hydra 10* record human dive

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Abstract During the 7.1-MPa hydrogen-helium-oxygen record human dive, we tested the hypothesis that the increased ambient pressure would alter the maximal muscle performance, specifically that breathing dense gas would lead to fatigue of the respiratory muscle. A group of hand muscles (adductor pollicis, AP) and the inspiratory muscles (IM) were studied in three professional divers. Maximal voluntary contractions (MVC) of AP and maximal inspiratory pressure ($P_{i_{max}}$) generated by IM were measured prior to the dive, during compression and decompression, and then 1 and 2 months after the dive. The decrease in MVC (−22%) was significant at 3.1 MPa, i.e. at the beginning of the introduction of hydrogen into the breathing mixture, whereas $P_{i_{max}}$ fell progressively during the dive and decompression (maximal $\Delta P_{i_{max}}$ = −55%), a significant reduction still being measured 1 month after the dive. The altered IM function was attributed to the consequences of long-term ventilatory loading, a condition associated with breathing a dense gas. The transient decrease in MVC of the skeletal muscle would indicate a possible effect of the hyperbaric environment, possibly the high partial pressure of hydrogen, on neuromuscular drive.

Key words Deep saturation dive · Hydrogen · Maximal voluntary contraction · Inspiratory muscles · Skeletal muscle

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Introduction

Deep sea diving by humans requires breathing gas mixtures, at an increased density which is proportional to the elevated ambient pressure. This has been reported to result in an increased airflow resistance during eupnoea and an associated increase in the work of breathing (Lenoir et al. 1990). Thus, diving may be considered to be a model of prolonged ventilatory loading, which may lead to fatigue of the respiratory muscles followed by ventilatory failure. Failure of the diaphragm associated with impaired transmission of muscle membrane potentials has already been demonstrated in cats under very high pressure (10.1 Mpa; Burnet et al. 1992). In humans, electromyograph signs of diaphragm fatigue have been shown during sojourns at 2.6 MPa (Derrien et al. 1990) and 4.6 MPa (Lenoir et al. 1990) in experiments using helium-oxygen and helium-nitrogen-oxygen mixtures. In addition, the high partial pressures of diluent gases (helium, hydrogen) may also affect neuromuscular motor drive. A hyperbaric low frequency tremor has been recorded in all muscle groups, including the diaphragm, when an helium-oxygen but not an helium-nitrogen-oxygen mixture has been used in humans (Lenoir et al. 1990) and cats (Burnet et al. 1992). This may have altered the motor drive to muscles and their mechanical performance. Moreover, in vitro studies in the phrenic nerve-to-diaphragm preparation have shown the existence of a partial neuromuscular block at high helium pressures (Kendig et al. 1976). Compared to helium, the use of hydrogen as a diluent gas reduces the density of the breathing mixture, improving the ventilatory mechanics. It also attenuates the excitatory effects of high pressure on the central nervous system (high pressure nervous syndrome; Brauer and Way 1970). Thus, the narcotic properties of hydrogen may affect the maximal voluntary contractions (MVC) through a central depressor effect.

During the 7.1-MPa hydrogen-helium-oxygen record human dive and the 2-month post-dive recovery period, we recorded MVC in the adductor pollicis muscle (AP) and the maximal inspiratory pressure ($P_{i_{max}}$) generated by the inspiratory muscles (IM). The aims of this study were to describe the consequences of a progressive increase in the work of breathing with increased gas density on inspiratory muscle function and to compare these data to those obtained in AP, a group of hand muscles which did not participate in the respiratory efforts. The persistence of any altered muscle performance after the dive was also examined.

Methods

Subjects

Control and post-dive measurements were performed in the Centre Hospitatier Universitaire Nord Respiratory Function Testing Laboratory in Marseille and the diving studies in the Experimental Hyperbaric Center of COMEX SA (Marseille). Three healthy professional divers participated in this experimental deep saturation dive. The protocol was approved by the Ethics Committee.

Protocol

Due to 18 different work schedules to complete during the dive, the three subjects were very busy and had in general nine tasks each day to perform including exercise tests.

No exercise protocols were planned for the day on which we measured muscle performances. Table 1 shows the physical parameters corresponding to the periods of diving when MVC and $P_{i_{max}}$ were measured. In all cases the inspired partial pressure of oxygen (PO_2) was 0.04 MPa. As indicated in Fig. 1, the dive began with helium in the mixture until a pressure of 2.1 Mpa was attained. Then hydrogen was added progressively until the absolute pressure reached 4.1 MPa and PH_2 was held constant (2 MPa) until the end of the sojourn at maximal pressure (7.1 MPa). The subjects breathed a helium-oxygen gas mixture when measurements were made during decompression at 0.9 MPa. One subject completed the whole protocol, including the soujourn at 7.1 MPa, whereas the two others decided to remain at a maximal pressure of 6.7 MPa. Measurements of muscle strength were not performed at 6.7 and 7.1 MPa.

Study of isometric muscle strength

All measurements were performed while the subjects were in a sitting position 3 h after stabilization of ambient pressure at the new level. The maximal force of thumb adduction was measured with apparatus that has previously been used (Derrien et al. 1990; Fontanari et al. 1996). All measurements were made on the left hand, the forearm resting in a supine position on a table mounted with a hangrip designed to hold firmly the four other fingers. A strap was placed around the proximal phalange of the thumb and was connected to an isometric strain gauge (Schenck LY 11, 0–50 daN). The force signal was displayed to the subject on an analogue voltmeter to provide visual feedback. For measurements of $P_{i_{max}}$, the subject wore a noseclip and breathed through a mouthpiece

Table 1 Experiment conditions of the dive, giving the ambient temperature, absolute ambient pressure, partial pressures of helium (PHe), hydrogen (PH_2), nitrogen (PN_2) and oxygen (PO_2) and the gas density corresponding to the epochs of testing the muscle function. The gas density was calculated at the corresponding ambient temperature

	Days of dive	Temperature (°C)	Pressure (Mpa)	PHe (Mpa)	PH_2 (Mpa)	PN_2 (Mpa)	PO_2 (Mpa)	Gas density ($g \cdot l^{-1}$)
Control	−31	20	0.1	0	0	0.979	0.021	1.2
Compression	1	25	0.2	0.08	0	0.080	0.04	1.5
	4	30	3.1	2.0	1.0	0.060	0.04	5.2
	11	31	5.6	3.5	2.0	0.060	0.04	8.4
	13	32	6.35	4.25	2.0	0.060	0.04	9.2
Decompression	39	29	0.9	0.8	0	0.040	0.06	2.1
Post-dive	68	20	0.1	0	0	0.979	0.021	1.2
	108	20	0.1	0	0	0.979	0.021	1.2

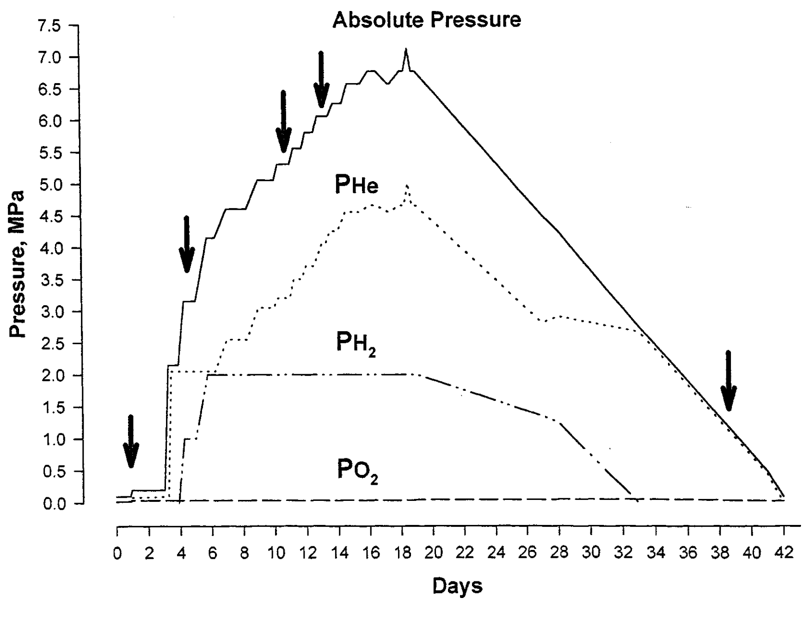

Fig. 1 Compression schedule (absolute pressure) and the time courses of changes in partial pressures of helium (PHe), hydrogen (PH_2) and oxygen (PO_2) during the Hydra 10 dive. *Black arrows* indicate the days when maximal voluntary contraction and maximal inspiratory pressure measurements were performed

connected to a short rigid plastic tube. The latter was connected to an Y-tube allowing the recording of mouth pressure by an electromanometer (Statham PM6TC, ±250 cm H_2O) and a mechanical manometer (Protais, 0–250 cm H_2O) providing visual feedback to the subjects. To prevent glottal closure during inspiratory manoeuvres, a small leak was produced by inserting a 18-gauge needle in the mouthpiece.

We asked the subject to execute Müller manoeuvres, which consisted in forced maximal inspirations from the residual volume (i.e. at the end of a maximal expiration) against an infinite resistance obtained by occlusion of the plastic tube. Development of $P_{\mathrm{i_{max}}}$ was considered as a quasi-isometric effort. Forced manoeuvres by AP and IM were repeated until three reproducible measurements could be maintained for 1 s.

Figure 1 indicates the times at which MVC and $P_{\mathrm{i_{max}}}$ were measured during the compression-decompression schedule. Measurements were first performed in control conditions (at 0.1 MPa whilst breathing room air), then during compression at 0.2 MPa in helium-oxygen and at 3.1, 5.6, and 6.35 MPa in helium-hydrogen-oxygen mixtures during each 9-h stay, during decompression at 0.9 MPa in a helium-oxygen mixture, and finally at 0.1 MPa (room air), 1 month and 2 months (only $P_{\mathrm{i_{max}}}$ measurements) after the end of the dive.

Statistical analyses

After assessment of the data for normality using a Kolmogorov-Smirnov test, a one-way analysis of variance for repeated measures (ANOVA RM) was used to show the effects of elevated pressure on MVC and $P_{\mathrm{i_{max}}}$. When ANOVA RM indicated the existence of a significant difference ($P < 0.05$) within experimental conditions, we used Dunnett's method as a post-ANOVA multiple comparison test. The Pearson correlation coefficient was used to test the strength of the relationships between the hydrostatic pressure and MVC or $P_{\mathrm{i_{max}}}$.

Results

As shown in Fig. 2, MVC of AP and $P_{\mathrm{i_{max}}}$ of IM tended to decrease during the dive. This effect was transient for AP and a significant decline ($P < 0.05$) was measured

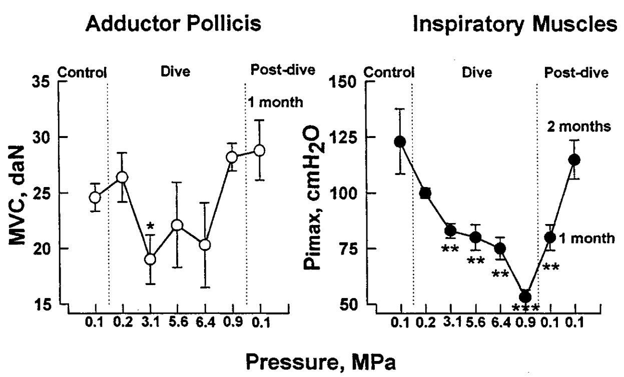

Fig. 2 Mean values and SEM of maximal force generated during maximal voluntary contractions (*MVC*) of the adductor pollicis and of maximal inspiratory pressure ($P_{\mathrm{i_{max}}}$) during Müller manoeuvres of the inspiratory muscles executed before (control), during the dive, and 1 and 2 months after the subjects returned to sea level (post-dive). Only maximal values of muscle strength and $P_{\mathrm{i_{max}}}$ were considered in each situation and each individual, thus each point was the mean of three data. *Asterisks* indicate that values differ significantly from controls: $*P < 0.05$, $**P < 0.01$, $***P < 0.001$

only at 3.1 MPa, i.e. 6 h after we began to add hydrogen to the inspired gas mixture. The MVC returned to control levels at 0.9 MPa during decompression. During the compression period, a significant negative correlation was found between $P_{\mathrm{i_{max}}}$ and the absolute ambient pressure ($r = -0.75$, $P < 0.001$). The relationship of $P_{\mathrm{i_{max}}}$ to ambient pressure made no sense when all data measured during compression, decompression and the post-dive recovery period were considered because the fall in $P_{\mathrm{i_{max}}}$ was accentuated during decompression ($\Delta P_{\mathrm{i_{max}}} = -55\%$) and persisted (−35%) for 1 month after the end of the dive (Fig. 2). Values of $P_{\mathrm{i_{max}}}$ had been restored to control levels 2 months after the end of the dive.

Discussion

The present results showed that maximal mechanical performance was impaired in one group of skeletal muscles and particularly in IM during the deep dive. For the AP muscles, the effects were only significant after addition of hydrogen to the breathing mixture. They disappeared during decompression when the subjects returned to breathing an helium-oxygen gas mixture. The fall in $P_{\mathrm{i_{max}}}$ progressed with the elevated pressure, persisted during decompression and also for at least 1 month after the dive.

The ambient conditions of this experimental dive differed from previous ones because of the maximal depth reached and also in the use of hydrogen as one of the diluent gases. The 0.04-MPa PO_2 was the same and even slightly lower than in other experimental and offshore dives. "It has been reported that no risk of pulmonary oxygen toxicity would be expected to occur at this PO_2 level (Clarke and Lambertsen 1971). This was confirmed in a companion investigation which did not find any post-dive changes in the forced vital capacity and the pulmonary diffusing capacity in the three volunteers.

Gelfand and Lambertsen (1978) have found no decrease in MVC of the handgrip (3.7 MPa) and biceps brachialis (6.2 MPa). The differences between the present observations and those of Gelfand and Lambertsen could be on the one hand that the fall in MVC was measured only at 3.1 MPa during our dive. On the other hand, we used an helium-hydrogen-oxygen mixture in the present study instead of helium-oxygen as in the other ones and while helium has been shown to accentuate the excitatory effects of high pressure on the central nervous system, hydrogen attenuates them (Brauer and Way 1970). The reduction of MVC could also have resulted from a lowered motivation of the subjects to generate maximal efforts due to stress resulting from a long period of confinement, but this cannot explain the significant decline in MVC measured only at the beginning of the dive.

Decreased MVC may also have resulted from an impaired excitation-contraction coupling. Indeed, in vitro studies in the phrenicnerve-to-diaphragm preparation have already shown the existence of a partial neuromuscular block under high pressure (Kendig and Cohen 1976). Another explanation for the decline in MVC whilst breathing dense gas mixtures may have been the central interactions between the respiratory afferent nerves and the cortical motor drive to the skeletal muscles. Indeed, we have shown in healthy individuals studied at atmospheric pressure that severe inspiratory loading reduced the motor drive to the skeletal muscles, including the AP muscle, during MVC manoeuvres (Fontanari et al. 1996). This was interpreted as the consequence of central interactions between the enhanced respiratory afferent nerve pathways and the cortical command to muscles. A severe ventilatory resistive loading was present during this dive (the inspired gas density was multiplied by 9). Thus, it is tempting to speculate that the activation of respiratory afferent nerves may alter the motor drive to skeletal muscles.

No significant decrease in $P_{\mathrm{i}_{\max}}$ has been reported during previous human dives in helium-oxygen gas mixtures (Derrien et al. 1990). However, the maximal ambient pressure was only 3.7 MPa in the dive reported by Gelfand and Lambertsen (1978) and 2.6 MPa in the dive reported by Derrien et al. (1990). No altered length-tension relationship in IM, due to an elevated functional residual capacity (FRC), could explain the progressive fall in $P_{\mathrm{i}_{\max}}$ during compression and decompression and also its persistence when the subjects returned to breathing ambient air at sea level. Indeed, any increase in FRC in response to the raised airway resistance due to breathing a dense gas should have been reduced during decompression and disappeared during breathing room air.

In addition, we have to remember that the subjects were asked to begin the Müller manoeuvres after a maximal expiration in order to minimize the consequences of changes in FRC. One possible explanation for the decrease in $P_{\mathrm{i}_{\max}}$ during this dive may be the existence of fatigue of the inspiratory muscles due to the prolonged and severe ventilatory loading. A recent study (Prezant et al. 1993) in rats exposed to long-term (24–28 weeks) continuous respiratory resistive loading, has shown that both the maximal tetanic tension and the peak twitch tension were reduced in the diaphragm. This may have also applied to the present observations on humans. However, the recovery from prolonged ventilatory loading was not examined during the rat study, so it cannot serve to explain the persistence of the lowered $P_{\mathrm{i}_{\max}}$ in our subjects during decompression and 1 month after the dive.

Another explanation for the reduced maximal mechanical performance of IM during this dive may have been the decreased transmission of myopotentials, i.e. a fatigue of peripheral muscles. Indeed, experiments in cats under very high pressure (10.1 Mpa; Burnet et al. 1992) have indicated the existence of peripheral fatigue in the diaphragm as assessed by the progressively declining amplitude of evoked compound muscle potential (M-wave), leading to an arrest of diaphragm contractions. Fortunately, no failure of spontaneous ventilation occurred during this dive but we may speculate that these circumstances of a prolonged increase in the work of the inspiratory muscle would have altered the maximal performance of IM. These harmful influences may require 1 month of unloaded breathing to disappear. These observations demonstrate the need to repeat $P_{\mathrm{i}_{\max}}$ measurements during and after human deep dives.

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References

Brauer RW, Way RO (1970) Relative narcotic potencies of hydrogen, helium, nitrogen and their mixtures. J Appl Physiol 29:23–31

Burnet H, Lenoir P, Jammes Y (1992) Changes in respiratory muscle activity in conscious cats during experimental dives at 101 ATA. J Appl Physiol 73:465–472

Clarke JM, Lambertsen CJ (1971) Pulmonary oxygen toxicity: a review. Pharmacol Rev 23:37–133

Derrien I, Lenoir P, Jammes Y (1990) Etude comparative des muscles diaphragme et adducteur du pouce lors de contractions statiques fatigantes à 25 ATA (abstract). Arch Int Physiol Biochim 98:A424

Fontanari P, Vuillon-Cacciuttolo G, Balzamo E, Zattara-Hartmann MC, Lagier-Teissonnier F, Jammes Y (1996) Resistive loaded breathing changes the motor drive to arm and leg muscles in man. Neurosci Lett 210:130–134

Gelfand R, Lambertsen CJ (1978) Muscle strength and coordination. In : Lambertsen R, Gelfand CJ, Clarke JM (eds) Work capability and physiological effects in $He\text{-}O_2$ excursions to pressures of 400-800-1200-1600 fsw. Predictive studies IV. University of Pensylvania, Philadelphia, pp E5/1-E5/13

Kendig JJ, Cohen EN (1976) Neuromuscular junction at hyperbaric pressures: pressure-anesthetic interactions. Am J Physiol 230:1244–1249

Lenoir P, Jammes Y, Giry P, Rostain JC, Burnet H, Tomei Ch, Roussos C (1990) Electromyographic study of respiratory muscles during human diving at 46 ATA. Undersea Biomed Res 17:121–137

Prezant DJ, Aldrich TK, Richner B, Gentry EI, Valentine DE, Nagashima H, Cahill J (1993) Effects of long-term continuous respiratory resistive loading on rat diaphragm function and structure. J Appl Physiol 74:1212–1219