Psychophysiological Responses of Pilots in Hypoxia Training at 7000 and 7500 m

Dongqing Wen; Lei Tu; Guiyou Wang; Zhao Gu; Weiru Shi; Xiaopeng Liu

INTRODUCTION: We compared the physiological responses, psychomotor performances, and hypoxia symptoms between 7000 m and 7500 m (23,000 and 24,600 ft) exposure to develop a safer hypoxia training protocol.

METHODS: In altitude chamber, 66 male pilots were exposed to 7000 and 7500 m. Heart rate and arterial oxygen saturation were continuously monitored. Psychomotor performance was assessed using the computational task. The hypoxic symptoms were investigated by a questionnaire.

RESULTS: The mean duration time of hypoxia was 323.0 ± 56.5 s at 7000 m and 218.2 ± 63.3 s at 7500 m. The 6-min hypoxia training was completed by 57.6% of the pilots and 6.1% of the pilots at 7000 m and at 7500 m, respectively. There were no significant differences in pilots' heart rates and psychomotor performance between the two exposures. The S_pO_2 response at 7500 m was slightly severer than that at 7000 m. During the 7000 m exposure, pilots experienced almost the same symptoms and similar frequency order as those during the 7500 m exposure.

CONCLUSIONS: There were concordant symptoms, psychomotor performance, and very similar physiological responses between 7000 m and 7500 m during hypoxia training. The results indicated that 7000-m hypoxia awareness training might be an alternative to 7500-m hypoxia training with lower DCS risk and longer experience time.

KEYWORDS: aerospace medicine, hypoxia training, physiological response, altitude.

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Hypobaric hypoxia is accepted as the most serious potential danger during flight[7,13] and pilots may suffer acute hypoxia due to high-altitude aviation activity. There is considerable consistency in the symptom complex experienced by an individual on repetitive exposure to acute hypoxia;[20] therefore, hypoxia training has been an important and well recognized component of aerospace physiological training programs. Military aircrew are usually exposed to 7620 m (25,000 ft) for no more than 5 mins in an altitude chamber every 3–5 yr in conventional hypoxia awareness training, which is considered the most effective for demonstrating the effects of hypoxia.[1,3,8] Chinese military aircrew underwent hypoxia training by exposing themselves to 7500 m (24,600 ft) in an altitude chamber, which is refreshed every 3 yr.

However, developing decompression sickness (DCS) with this training remains a major concern for the health of pilots.[9,12,19] Literature review shows that altitude chamber induced DCS has approximately a 0.25% incidence.[6,15] Although incidence of DCS with hypobaric training is reported to be low, some serious DCS symptoms are generally considered unacceptable. For reducing risks of decompression sickness, alternative methods have been developed, such as breathing a low oxygen gas mixture at lower altitude, even at ground.[10,18,21] The degree of pilots' hypoxia in all alternative methods is equivalent to breathing air at 25,000 ft.[10,18,21] Few studies on a lower degree of hypoxia applied to fighter pilots were reported.

The incidence and severity of DCS decreases with decreasing altitude. So we developed an alternative of 6-min 7000 m (23,000 ft) exposure that allowed hypoxia training to be safer and more effective. For demonstrating the safety and effectiveness of 7000 m exposure, we compared the physiological responses, psychomotor performances,

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and hypoxia symptoms of hypoxia awareness training between 7000 m and 7500 m.

METHODS

Subjects

Chosen as subjects for the study were 66 healthy male pilots serving in the China Air Force (age 26.9 ± 2.7 yr, flight time 614.2 ± 389.6 h). All subjects signed informed consent statements which outlined the purpose of the experiment and the protocols. This form also informed subjects of their rights to withdraw at any time without prejudice. All of the subjects were questioned about their current health status and accepted medical examination to ensure they could withstand the low pressure and hypoxia in an altitude chamber. None of them had any history of illness, particularly in relation to sinuses and ears, blood donation, and scuba diving, in the preceding week or flying above 10,000 ft (3048 m) in the preceding 24 h. Ethical approval to conduct the study was provided by the Air Force Medical Center research ethics committees (No. 2020-120-YJ01).

Equipment

All experiments were conducted in an altitude chamber at the Air Force Medical Center, Beijing, China.[22] Heart rate (HR) was continuously monitored using a Wireless Multi-Parameter Telemetry System (Beijing H&L Medical Science and Technology Ltd., Beijing, China). Electrocardiogram (ECG) was continuously displayed using three standard limb leads. Peripheral arterial oxygen saturation was continuously measured by a fingertip pulse oximeter (OnyxOR II 9550, Nonin Medical, Inc., Plymouth, MN, USA) with the probe on the index finger. Psychomotor performance was assessed using the self-designed computational task throughout the period of training, which requested subjects keep subtracting 4 or 3 alternately from 1000. The correct calculation per minute and the rate of correct calculation were recorded. Pilots practiced the task at least three times prior to their exposure to hypoxia to minimize any learning effects.

Procedure

The 66 male pilots were randomly and averagely divided into a 7000 m (23,000 ft) exposure group or 7500 m (24,600 ft) exposure group. They were blinded as to which exposure they were receiving. The subjects were seated in the altitude chamber and breathed air. The chamber decompressed from ground level to 2500 m (8202 ft) at $30\ m \cdot s^{-1}$ ($98.4\ ft \cdot s^{-1}$) and rapidly decompressed from 2500 m to 5500 m (18,045 ft) in 1 s. The subjects prebreathed 100% oxygen for denitrogenation while completing the computational task at 5500 m for 5 min, and then the subjects were decompressed to 7000 m or 7500 m at $30\ m \cdot s^{-1}$, continuing to breathe 100% oxygen. When the altitude destination was reached, subjects were asked to take off their oxygen masks and started the computational task under the guidance and supervision of an observer inside the chamber. If termination signs appeared, or 6-min hypoxia duration was reached, masks were replaced to perform recovery. Once the recovery from hypoxia was complete in all subjects, the chamber was recompressed to ground level at $15\ m \cdot s^{-1}$ ($49.2\ ft \cdot s^{-1}$). The total time above 7000 m and 5500 m was controlled to be within 30 and 60 min, respectively. During descent, the subjects were requested to complete a questionnaire related to hypoxia symptoms. All physiological parameters collected during the final 10 s of each minute at desired altitude were used for statistical analysis.

An air force physician, experienced in hypoxia training, supervised all subjects. Hypoxia training was terminated after 6-min hypoxia exposure or upon any of the following.

- The subject requested cessation of hypoxia.
- The subject failed to respond to the computational task for a continuous period of 15 s.
- Arterial oxygen saturations fell below 65%.
- A sudden fall in heart rate of more than 20 bpm.
- A decision by the physician to end the hypoxia.

Statistical Analysis

Values are expressed as means ± SD. Survival analysis was used for the comparison of duration time between 7000 m and 7500 m exposure. The percentage of subjects enduring hypoxia of different times between 7000 m and 7500 m exposure were tested by Chi-squared test. Unpaired *t*-test was used to compare differences in HR and S_pO_2. Paired *t*-test was used to compare correct calculation per minute between the prebreathe period at 5500 m and the hypoxia period at 7000 m or 7500 m. The Wilcoxon matched-pairs signed rank test was used to compare correct calculation rate between the prebreathe period at 5500 m and the hypoxia period at 7000 m or 7500 m. An unpaired *t*-test was used to compare the changes of correct calculation per minute between 7000 and 7500 m exposure. Mann-Whitney analysis was used to compare the changes of correct calculation rate between 7000 and 7500 m exposure. All analyses were performed using GraphPad 6.0. A confidence interval of $P < 0.05$ was assumed.

RESULTS

The minimum hypoxia endurance time was above 173 s and the mean time was 323.0 ± 56.5 s in the 7000 m (23,000 ft) group, as compared with the 120 s and 218.2 ± 63.3 s in the 7500 m (24,600 ft) group. The endurance time of hypoxia during the 7000 m exposure was significantly longer than that during the 7500 m exposure ($P < 0.0001$) (**Fig. 1**).

All subjects withstood 2-min hypoxia training and the number of subjects enduring hypoxia training decreased with hypoxia time. The number of subjects who endured longer than 3 min of hypoxia during the 7000 m exposure were significantly higher than during the 7500 m exposure ($P < 0.01$) (**Table I**).

Fig. 2 shows the time course of mean HR for all subjects during exposure to 7000 m and 7500 m. Compared with HR at

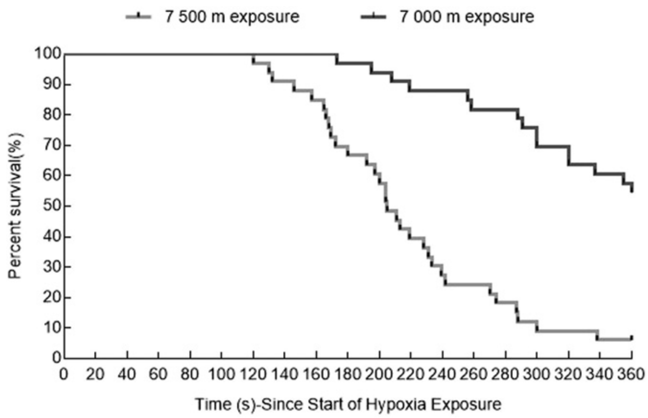

Fig. 1. Hypoxia endurance time at 7000 m and 7500 m (23,000 and 24,600 ft) exposure.

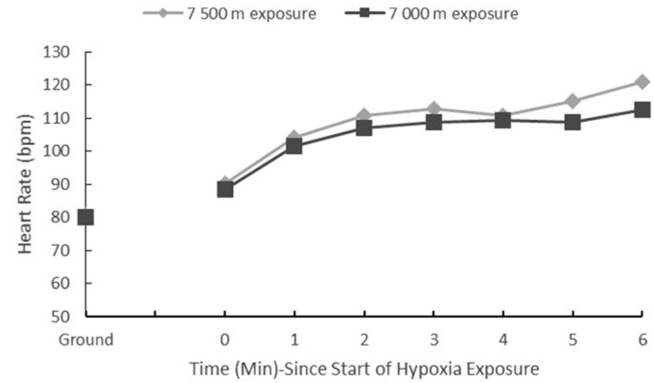

Fig. 2. Mean heart rate response during 7000 m and 7500 m (23,000 and 24,600 ft) exposure.

ground, the mean HR increase during the 4 min of 7000 m and 7500 m exposure was 26.5 ± 10.2 bpm and 28.2 ± 13.0 bpm, respectively, and the difference in HR increase was insignificant between 7000 and 7500 m exposure ($P > 0.05$). Compared with HR during prebreathe at 5500 m (18,045 ft), the mean HR increase during the 4 min of the 7000 and 7500 m exposure was 18.0 ± 9.5 bpm and 18.9 ± 9.9 bpm, respectively, and the difference in HR increase was insignificant between 7000 and 7500 m exposure ($P > 0.05$).

Fig. 3 shows the time course of mean S_pO_2 for all subjects during exposure to 7000 and 7500 m. The S_pO_2 response at 7500 m was significantly severer than at 7000 m during 4 min of exposure ($P < 0.05$). The mean minimum S_pO_2 reached was 70.1 ± 3.2% at the sixth minute of the 7000 m exposure and 68.1 ± 4.3% at the fourth minute of the 7500 m exposure.

Fig. 4 shows the percentage of subjects who experienced 16 commonly reported symptoms of hypoxia during the 7000 and 7500 m exposure. The frequency order of symptoms was seen to be broadly the same in both types of hypoxia. The top three frequently reported symptoms were dizziness, thinking slowly, and lack of concentration in both types of exposure.

The correct calculation speed and rate decreased gradually with the duration of exposure in both types of hypoxia. As compared with the prebreathe period at 5500 m, the correct calculation per minute decreased from 13.66 ± 3.47 times to 11.66 ± 3.22 times ($P < 0.0001$) and correct calculation rate decreased from 96.5 ± 3.9% to 91.2 ± 5.3% during the 7000 m exposure ($P < 0.0001$). For the same comparison during the 7500 m exposure, the correct calculation per minute decreased from 14.01 ± 4.10 times to 11.41 ± 3.71 times ($P < 0.0001$) and correct calculation rate decreased from 96.9 ± 3.5% to 89.1 ± 8.7% ($P < 0.0001$). There was no statistical significance in the changes of correct calculation per minute ($P > 0.05$) and correct calculation rate ($P > 0.05$) between 7000 and 7500 m exposure (**Table II**).

Table I. Number (Percentage) of Pilots Enduring Hypoxia at 7000 m and 7500 m (23,000 and 24,600 ft).

HYPOXIA TIME	7000 M EXPOSURE ($N = 33$)	7500 M EXPOSURE ($N = 33$)
120 s	33 (100.0%)	33 (100.0%)
180 s	32 (97.0%)	23 (69.7%)
240 s	29 (87.9%)	9 (27.3%)
300 s	25 (75.6%)	4 (12.1%)
360 s	19 (57.6%)	2 (6.1%)

DISCUSSION

This study found that 7000 m (23,000 ft) exposure produced similar physiological and performance responses and identical symptoms with similar frequency order with 7500 m (24,600 ft) exposure for the purposes of hypoxia training. Hypoxia training at 7000 m had the advantage in that it provided the trainee with a lower risk of DCS and longer hypoxia time.

The resting subject may experience circulatory failure, central nervous system failure, convulsions, cardiovascular collapse, and even death when they are exposed above 6000 m (20,000 ft).[7] The conventional hypoxia awareness training requires military aircrew be exposed to 7500 or 7600 m (24,660 or 24,935 ft) to demonstrate the effects of hypoxia.[11,16] Both 7000 m exposure and 7500 m exposure could lead to the critical stage of acute hypoxia, in which there is almost complete mental and physical incapacitation, resulting in rapid loss of consciousness, convulsions, and finally failure of respiration and even death. The inspired partial pressure of oxygen (P_IO_2) of

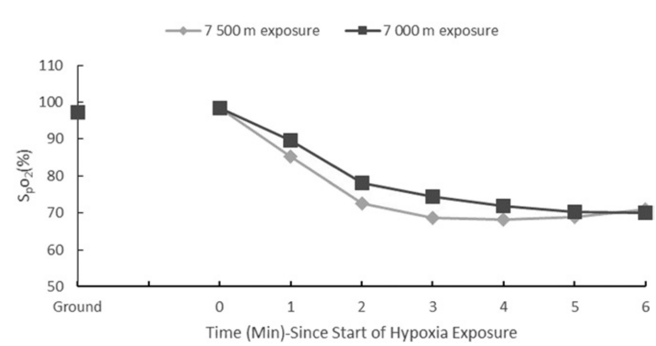

Fig. 3. Mean S_pO_2 response during exposure to 7000 m and 7500 m (23,000 and 24,600 ft).

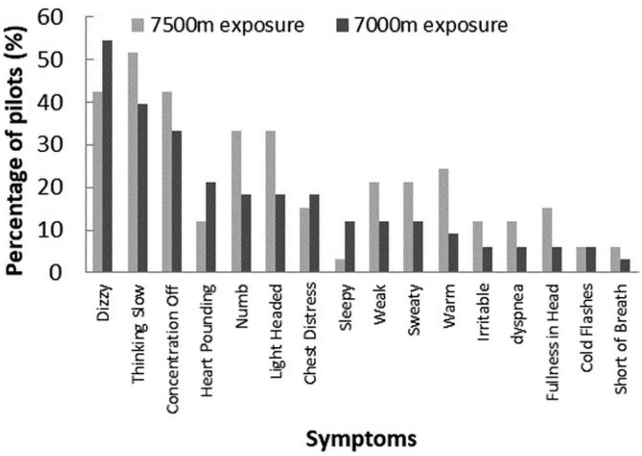

Fig. 4. Frequency of hypoxia symptoms during 7000 m and 7500 m (23,000 and 24,600 ft) exposure.

pilots in 7000 and 7500 m exposure is 54.6 mmHg and 50.2 mmHg, respectively, based on Dalton's law of partial pressures and correcting for water vapor pressure (47 mmHg at 37°C): P_IO_2 (tracheal, fully humidified) = F_IO_2 (P_B − 47). The 4.4-mmHg difference of inspired partial pressure of oxygen led to a similar change in heart rate and a slightly different change in S_pO_2 within a 4-min exposure at 7000 and 7500 m, which prolonged the duration time at 7000 m.

The volume of oxygen extracted from arterial blood became progressively limited at 7000 m and 7500 m and an increased cardiac output was required to meet pilots' oxygen demand.[13] Since stroke volume remained unchanged as cardiac output increased, there was a proportional increase in HR. HR increase during the 7000 and 7500 m exposure was less than during the 7600 m exposure.[18] In our study, only four pilots (12.1%) in the 7500 m exposure could endure hypoxia for 5 min; therefore, we only compare the HR change in the 4-min period between the 7000 and 7500 m exposure. The HR change was similar in the 4-min period during both kinds of hypoxia. HR increased by 15–25% and 27–39%, respectively, as compared with that during breathing oxygen at 5500 m (18,045 ft) and during breathing air at ground level. This may have been due to the anxiety-producing aspects of the altitude chamber experience, which was supported by the HR difference between breathing oxygen at 5500 m and breathing air at ground level.

Typical blood oxygen saturation for resting subjects acutely exposed to altitude is 66% when alveolar oxygen tension is 29 mmHg, which is unacceptable for pilots to avoid the potential catastrophic consequences of hypoxia.[7] In our study, the training session was terminated via oxygen mask replacement when pilots' arterial oxygen saturation dropped below 65%. Such criterion was consistent with a conventional hypoxia training program.[2] S_pO_2 was a sensitive and stable index in response to hypoxia. Therefore, the S_pO_2 declined faster at 7500 m than at 7000 m. It is interesting to note that S_pO_2 fell to its lowest level at 4 min of 7500 m exposure while S_pO_2 did so at 6 min of 7000 m exposure. This may be due to only 4 of 33 pilots (12.1%) being able to endure more than 5 min during the 7500 m exposure. These pilots were thought to have a better ability to endure acute hypoxia than others during the 7500 m exposure. Hence, their S_pO_2 declined more slowly and could maintain a relatively higher level than others. That is why the mean S_pO_2 was lower at 4 min than at 6 min during the 7500 m exposure.

In our study, the maximum hypoxia time was limited to 6 min, which was 1 min longer than the documented endurance time of 270 ± 96 s at 7620 m (25,000 ft).[7] During hypoxia, pilots ceasing hypoxia training increased with increasing time of exposure. There were 14 pilots (42.4%) who terminated hypoxia training and the mean hypoxia time was 323.0 ± 56.5 s in the 7000 m group, while 31 pilots (93.9%) terminated hypoxia training and the mean hypoxia time was 218.2 ± 63.3 s in the 7500 m group. Subjects in the 7000 m exposure had about 100 s longer endurance time than those in the 7500 m exposure, but there was no evidence to show that longer exposure resulted in extra physical effects and no subject complained of any discomfort after training. Firstly, the total time above 7000 m and above 5500 m is no more than 30 min and 60 min, respectively, in our study, which was consistent with the conventional training program. Secondly, the administration of oxygen to a hypoxic subject usually results in a rapid and complete recovery.[7] None of the subjects in the 7000 m exposure complained of any discomfort after training and this also verified our corollary.

Hypoxia had a negative effect on psychomotor performance.[18] Hypoxia led to a 14.6–18.6% decrease of correct calculation per minute and a 5.5–8.0% decrease of correct calculation rate. These indicated our psychomotor performance test was sensitive to hypoxia. The psychomotor performance tests revealed no significant difference between the two hypoxia regimens.

In our study, pilots experienced 16 commonly reported symptoms which were basically consistent with hypoxia symptoms reported by Slef[17] and Singh.[18] The hypoxia symptoms at 7000 m mirrored those experienced at 7500 m, though the frequency of these symptoms was slightly different, which did not impact the symptom experience compared with the 7500 m exposure.

We concluded two major advantages of the 7000 m exposure as compared with 7500 m. Firstly, 7000 m (23,000 ft) exposure enabled lower DCS risk because the critical supersaturation ratio[7] decreased from 2.11 to 1.92 when altitude descended from 7500 m to 7000 m. There were no decompression sickness cases reported during the 7000 m

Table II. Correct Calculation per Minute and Correct Calculation Rate During Hypoxia.

ALTITUDE	CORRECT CALCULATION PER MINUTE		CORRECT CALCULATION RATE (%)	
	DURING PREBREATHE	DURING HYPOXIA	DURING PREBREATHE	DURING HYPOXIA
7000 m	13.66 ± 3.47	11.66 ± 3.22	96.5 ± 3.9	91.2 ± 5.3
7500 m	14.01 ± 4.10	11.41 ± 3.71	96.9 ± 3.5	89.1 ± 8.7

7000 m = ~23,000 ft and 7500 m = ~24,600 ft.

hypoxia training, compared with the 0.11–0.25% incidence in various populations and the mean incidence of 0.17% at 7600 m (24,935 ft) and above.[4,5,14,15]

Secondly, pilots have a longer time to experience their individual symptoms and physiological and psychomotor responses to hypoxia. The mean hypoxia training time was prolonged from 218.2 s at 7500 m to 323.0 s at 7000 m and the shortest hypoxia training time was prolonged from 120 s to 173 s. This avoided terminating hypoxia training in a very short time, which is beneficial for demonstrating hypoxia to all participants with different hypoxia endurance.

Possible weaknesses in our experimental design may have resulted from the 6-min hypoxia time. In the 7000 m exposure, 57.6% of the pilots still maintained 65% or higher S_pO_2 after a 6-min exposure when hypoxia training was terminated, which indicated it is necessary to investigate physiological responses for a longer time at 7000 m exposure in the future.

In general, the 7000 m regimen maintained hypoxia training efficiency, a safer critical supersaturation ratio, and a longer experience time as compared with the 7500 m regimen. The minor physiological differences do not impact on the symptom experience or training value. Therefore, we believe that the 7000 m regimen could be a safe and efficient alternative to the conventional 7500 m hypoxia training in an altitude chamber.

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