Original article

Psychophysiological response of fighter aircraft pilots in normobaric hypoxia training

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Summary

Hypoxia remains the most important hazard in high altitude flights as it is a rare condition presenting itself without consistent symptoms that prevent aircrew from warning in advance. An acute ventilatory response is the mechanism that works to get back oxygen concentration homeostasis, causing hypocapnia and a respiratory alkalosis, which causes breathing muscles fatigue. Some authors have identified previous training on hypoxia contexts as essential to avoid accidents but it is still poor know the effect of hypoxia exposition in the psychophysiological and cognitive functions. We proposed the present study with the aims of to study the effect of hypoxia training in cortical arousal, autonomic modulation and muscle strength. We analysed 3 male fight pilots of the Spanish Army before and after normobaric hypoxia training. The following variables were reported: subjective perceived stress (SPS), rated perceived exertion (RPE), cortical arousal (Critical Flicker Fusion Threshold (CFFT)), isometric handgrip strength, blood oxygen saturation (SaO_2), heart rate (HR) and spirometry values (forced vital capacity (FVC), forced expiratory volume in 1 second (FEV_1), peak expiratory flow (PEF)). The effect size (ES) was tested by Cohen's D. No variable presented significant differences between tests. SPS, RPE, handgrip strength, heart rate and FVC increased after training. FEV_1, PEF, CFFT and SaO_2 decreased during the training. These results agreed with previous research in military population. Normobaric hypoxia training produces a decreased tendency in cortical arousal and an increase in perceived effort, stress, and increased tendency in muscular strength. These results can help to find specific training for better prepare fight pilots for hypoxic threats.

Key words:
Hypoxia. Pilots. Cortical arousal. Fatigue.

Respuesta psicofisiológica de pilotos de caza en entrenamiento de hipoxia normobárica

Resumen

La hipoxia es el peligro más importante en los vuelos a gran altitud, debido a que es un estado poco frecuente y se presenta sin síntomas consistentes que impiden una alerta temprana. Una respuesta ventilatoria aguda es el mecanismo que trabaja para recuperar la homeostasis de la concentración de oxígeno, causando hipocapnia y una alcalosis respiratoria, provocando fatiga en los músculos respiratorios. Algunos autores han identificado que el entrenamiento previo en contextos de hipoxia es esencial para evitar accidentes pero todavía es pobre el conocimiento existente sobre el efecto de la exposición a hipoxia en las funciones psicofisiológicas y cognitivas. El objetivo de esta investigación fue estudiar el efecto del entrenamiento en hipoxia en la activación cortical, la modulación autonómica y la fuerza muscular. Analizamos 3 pilotos de caza del Ejército del Aire antes y después del entrenamiento de hipoxia normobárica. Se registraron las siguientes variables: estrés subjetivo percibido (RPE), esfuerzo percibido (RPE), excitación cortical (Critical Flicker Fusion Threshold (CFFT)), fuerza isométrica de agarre, saturación de oxígeno en sangre (SaO_2), frecuencia cardíaca (FC) y espirometría (capacidad vital forzada (CVF), volumen espiratorio forzado en 1 segundo (FEV_1), flujo espiratorio máximo (PEF)). El efecto de muestra fue analizado mediante la D de Cohen. Ninguna variable presentó diferencias significativas entre los tests. SPS, RPE, fuerza isométrica, frecuencia cardiaca y FVC aumentaron con el entrenamiento. FEV_1, PEF, CFFT y SaO_2 disminuyeron con el entrenamiento. Estos resultados coincidieron con investigaciones previas en población militar. El entrenamiento de hipoxia normobárica produce una tendencia disminuida en la excitación cortical y un aumento en el esfuerzo percibido, el estrés y la tendencia creciente en la fuerza muscular. Estos resultados pueden ayudar a encontrar entrenamiento específico para preparar mejor a los pilotos de caza ante la hipoxia.

Palabras clave:
Hipoxia. Pilotos. Activación cortical. Fatiga.

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Introduction

The effect of altitude exposition in human body systems have been traditionally studied as they represent a source of stress for human beings[1,2]. Mechanical, psychological and physiological risks have been reported and studied although hypoxia remains the most important hazard in high altitude flights[3]. Moreover, hypoxia is a rare condition presenting itself without consistent symptoms that prevents aircrew from warning in advance, fact that can lead to fatal aviation incidents[4].

Hypobaric hypoxia (resulting from the air pressure reduction with increasing altitude) produces a lower alveolar oxygen partial pressure, reducing oxygen partial pressure in the arterial blood. An acute ventilatory response is the mechanism that works to get back oxygen concentration homeostasis, causing hypocapnia and a respiratory alkalosis[3], which causes breathing muscles fatigue[5]. The individual tolerance of low blood oxygen concentrations defines the symptoms experienced, most of them caused by cerebral oxygen delivery. These symptoms include: psychomotor impairment, impairment of cognitive function, visual impairment, psychological stress and anxiety, shortness of breath, paraesthesia, headache, dizziness, nausea, light-headness and tachycardia[4].

Some authors have identified previous training on hypoxia contexts as essential to avoid accidents facing cabin depressurization incidents[6,7]. Psychomotor impairment is one of the acute hypobaric hypoxia symptoms, as it affects aircrew postural control, increasing the postural sway as altitude augments[8]. Memory impairment has been reported, both in short-term[9] and working memory capacity[9,10], especially above 25000 feet altitude, where aircrew unawareness of their inability to maintain performance was underlined. Other parameters as cortical arousal seems to be impaired during hypoxia; perceptual ability (measured by the flicker fusion threshold) suffers an exertion and causes fatigue in pilots during hypoxia exposition[11]; and logic reasoning that was impaired in altitude, as well as the increased number of math test errors in hypoxic conditions[12,13]. Also, the autonomic modulation has been studied by some authors: although hypoxia clearly affects autonomous system, there is still some controversy on the opposite psychological symptoms (anxiety, depression or euphoria). Heart Rate Variability (HRV) tends to be the preferred instrument to measure this variable, as it is a non-invasive method. HRV has been reported to increase in aircrew population under hypoxic conditions, showing sympathetic nervous system prevalence[14-16]. To highlight the importance of hypoxia in altitude, autonomic modulation acts in reverse at 4574 m with hyperoxic conditions, showing parasympathetic nervous system prevalence as reported in one of these studies with aircrew[17].

All of these facts are factors that can affect pilots in high altitude, but is still poor know the effect of hypoxia exposition in the psychophysiological and cognitive functions. We proposed the present study with the aims of to study the effect of hypoxia training in cortical arousal, autonomic modulation and muscle strength.

Material and method

Participants

We analysed 3 male pilots of the Spanish Army that belonged to Group I (pilots of any type of aircraft) and with a qualification of "fit" according to the periodic medical examination as recorded in the ministerial order 23/2011. In addition, during the research they were carrying out the periodic aeromedical training included in the ministerial order 23/2011 and the STANAG 3114 "Aeromedical Training of Flight Personnel" (NATO regulations). Soldiers were equipped with standard uniforms, boots, and flying operative helmet and mask. Before starting the research, the experimental procedures were explained to all the participants, who gave their voluntary written informed consent. The procedures conducted in the present research were designed following the Declaration of Helsinki and approved by the Medical Service of the Aerospace Medicine Instruction Centre of Spanish Air Force.

Instrumentation and study variables

Before and after the hypoxia training, the following parameters were analysed in this order:

- Subjective perceived stress was assessed using a 0-100 scale.
- Rated Perceived Exertion was analysed through the Borg scale (values ranged from 6 to 20).
- Cortical arousal was measured through the Critical Flicker Fusion Threshold (CFFT) in a viewing chamber (Lafayette Instrument Flicker Fusion Control Unit Model 12,021) following the procedures conducted in previous studies[18].
- Isometric handgrip strength by a grip dynamometer (Takei Kiki Koyo, Japan).
- Blood oxygen saturation (BOS) and heart rate (HR) were measured with a normobaric hypoxia training system with these characteristics:
  - Simulated altitude levels: 0-27000 feet.
  - Hypoxic and hyperoxic air generation. Oxygen margins: 6.5%-40.0%
  - Membrane system for the separation of hypoxic and hyperoxic air.
  - Flexible system for configuration of flight profiles.
  - Cognitive battery to configure and record the evolution of cognitive performance depending on the state of hypoxia.
  - Continuous recording of physiological variables including BOS and HR.
- Spirometry values of forced vital capacity (FVC), forced expiratory volume in 1 second (FEV_1) and peak expiratory flow (PEF) were measured using a spirometer QM-SP100 (Quirumed, Spain) performing a maximum inhale-exhale-inhale cycle as previous research[19].

Procedure

The pilots performed the hypoxia training seating in front of a touch screen computer while completing cognitive tests that were repeated with different instances of the same test in a 2 minute interval basis.

Altitude changes were defined for three intervals depending of the simulated altitude. The characteristics of each period were: i) 3 minutes at 0 feet (0 metres); ii) 8 minutes at 16300 feet (5000 metres); iii) 10 minutes at 24700 feet (7500 metres).

The training was supervised by the Medical Service and the Training Flight Instructor of the Aerospace Medicine Instruction Centre. The end of the training could occur if one of these facts happened: i) Medical

Service noticed health risk; ii) Soldier noticed health risk; iii) Sudden HR raise detected by the training system; iv) Blood oxygen saturation below 60% detected by the training system.

Statistical analysis

The SPSS statistical package (version 21.0; SPSS, Inc. Chicago, Illinois) was used to analyse the data. Normality and homoscedasticity assumptions were checked with a Shapiro-Wilk test. Differences between pre and post samples were analysed using a non-parametric Wilcoxon test because the low sample analysed. Spearman test was used to analyse correlation between variables. The effect size (ES) was tested by Cohen's D [ES = (Post-test mean-Pre-test mean)/Pre-test SD]. The level of significance for all the comparisons was set at $P < .05$.

Results

The results are reported as mean±SD. In Table 1 are shown the pre-post results of the physiological and psychological variables studied in both pre and post tests.

No variable presented significant differences between tests. A large effect size was reported for Subjective Stress Perception and Rated Perceived Effort, which augmented during the training. Handgrip Strength and HR, also increased but presented a small effect size. The last reported raised variable was the FVC, which had a moderate effect size. FEV_1, PEF, CFFT and SaO_2 decreased during the training. A large effect size was found for SaO_2. A small effect size was found for CFFT. Finally, a trivial effect size was reported for FEV_1 and PEF.

Discussion

The aim of this research was to study the effect of hypoxia training in cortical arousal, autonomic modulation and muscle strength in fight pilots. The results showed a tendency towards the decrease of cortical arousal and rise in perceived effort and stress. They also reported a trend to increased upper body strength as an autonomic response facing hypoxic stress.

Oxygen saturation decreased and mean SaO_2 after hypoxia was similar to some studies[11,14,16], but higher than in other mild hypoxia research[13]. These differences could be explained taking into account the goal of each study: in mild hypoxia training the maximum altitude rarely surpass a maximum altitude of 4000 m. A decreased SaO_2 usually has a negative effect on the cortex performance. The analysis of cortical arousal was previously analysed in pilots, reporting a significant decreased value of CFFT after hypoxia training in hypobaric chamber[11]. Taking into account the effect size, these results are similar to ours and suggest that normobaric hypoxia training could also fatigue the Central Nervous System (CNS) and affect cortical arousal in aircrew[20]. It could be related with the lower oxygen availability in these situations, fact that produces a decrease in cortical arousal because of the lower access to oxygen of CNS cells[21]. The decrease in cortical arousal after the third series has also been evaluated by Clemente *et al.*, (2010) after performing a RSA (repeated sprint ability) maximum speed test[22], and after performing a cycling test to exhaustion in triathletes[23]. In contrast, during a maximal oxygen uptake cycling test[24], an incremental maximum cycling test[25], a 30 min maximum cycling test[26], a 70% maximal oxygen uptake cycling trial[27] and a 1RM squat test[28] cortical arousal increased.

Heart rate has been previously monitored in aircrew hypoxia training researches, reporting increased in cardiovascular response after the hypoxia exposition[11,14-16] as a physiological adaptation to lack of oxygen[3]. The small effect size of our sample suggest that normobaric hypoxia training could decrease the HR augmentation as there are no significant differences comparing with signification found in previous hypobaric chamber studies[11,14,16]. The increased HR after training was also lower than in a study of automatic parachute, what suggest that the reminiscence of the sympathetic activation during the training is higher when aircrafts are used to practice. Future studies with a higher number of participants have to confirm these findings. RPE and Subjective Stress Perception increases during training can be related to CNS fatigue and autonomic modulation. These results agree with previous research conducted in both normobaric[11] and hypobaric hypoxia[14,16] and reinforce the assumption of hypoxia-induced changes in CNS functions.

Handgrip strength slightly improved after hypoxia training, which seems to partially exert during hypoxic conditions as an adaptation in

Table 1. Results of study variables.

Variable	Units	Pre	Post	Z	P	Cohen's D
SSP	0-100 rank	6.7±5.8	33.3±28.9	-1.414	.157	4.59
RPE	6-20 rank	7.7±1.5	12.7±1.5	-1.604	.109	3.27
HG Strength	kg	44.0±2.0	45.3±4.5	-.816	.414	0.67
FVC	l	4.9±0.4	5.5±0.3	-1.604	.109	1.23
FEV 1	l	4.0±0.3	3.9±0.9	.000	1.000	-0.41
PEF	l	8.6±2.1	7.7±2.6	-1.069	.285	-0.46
SaO_2	0-100%	97.0±1.0	77.7±3.8	-1.604	.109	-19.33
HR	bpm	78.3±13.0	85.7±8.0	-1.069	.285	0.56
CFFT	Hz	34.5±2.2	34.3±2.1	-.535	.593	-0.84

SSP: Subjective Stress Perception; RPE: Rated Perceived Exertion; HG: Handgrip; FVC: Forced Vital Capacity; FEV_1: Forced Expiratory Volume in 1 second; PEF: Peak Expiratory Flow; SaO_2: Oxygen Saturation; HR: Heart Rate; CFFT: Critical Flicker Fusion Threshold.

which the sympathetic nervous system is activated and prepares the body for any hazardous situation[29]. This uncertainty makes the sympathetic system to foster muscle activation which can cause an increase in muscle strength, as shown in previous research[30].

Something similar happened in terms of breath muscles strength: FVC slightly improved as a result of an activation of breath muscles after an external threat was perceived. As a result, the autonomic nervous system releases catecholamine into blood stream that produces an increase in strength, as shown in previous research with soldiers[31]. But explosive-related variables (FEV_1 and PEF) slightly decreased, probably because of fatigue after hypoxic conditions, as previously reported at altitude[5].

Study limitations and future research

The main limitation found in this study is the small sample size and the difficulties to access fighter pilots, as they belong to an elite group among military forces. Secondly, due to resource availability, there were no measurements of stress hormones (as cortisol, adrenaline, etc.), autonomic modulation and electroencephalography. Future studies should take into account these variables as they could help to better understand psychophysiological response to hypoxia.

Practical application

These results can help to find specific training for better prepare fight pilots for hypoxic threats. The data collected in the present work is of vital importance in order to define specific training systems as well as operational protocols for flight personnel in the development of their different tasks in their job, both in military and civil aviation. Training should be specific, individualized, prevent injuries and directed by qualified personnel. While many of the research agree on the need to be trained to withstand the stress of flight crews, many of the recommendations still lack adequate specificity as there is a need to take into account the actual needs of the pilot population.

Conclusion

Normobaric hypoxia training produces a decreased tendency in cortical arousal and an increase in perceived effort, stress, and increased tendency in muscular strength.

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