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Hypobaric Hypoxia in Aircrew: a brief review on etiology, risks, and preventive exercises

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ABSTRACT

Hypobaric hypoxia is caused by insufficient oxygen in the crew due to low atmospheric pressure. It causes hypoxemia and the symptoms of hypobaric hypoxia progressively develop, making the crew unable to perform executive functions. Aircraft accidents due to the development of hypobaric hypoxia in the crew have caused hundreds of casualties in the modern era of aviation, involving different aircraft and in other countries. To prevent such accidents, the aircrews perform simulated hypobaric chamber exercises periodically, in this way, it is possible to introduce the symptoms of hypobaric hypoxia to them in a safe and controlled atmosphere. Consequently, this allows them to remember hypoxia symptoms during an eventual aviation incident. The interval between hypobaric chamber exercises varies between countries. Although they are not mandatory, it is suggested that an interval of between three and six years between hypoxia exercises is appropriate to maintain flight safety concerning hypoxia symptoms. However, it is important to be aware that there is intra- and inter-personal variability in hypobaric hypoxia symptoms.

Keywords: Hypobaric; Hypoxia; Hypoxia Awereness Training; Hypoxia symptoms; Aircrew.

Hipoxia hipobárica en tripulantes: una breve revisión sobre etiología, riesgos y ejercicios preventivos

RESUMEN

La hipoxia hipobárica se produce por la falta de oxígeno en la tripulación debido a la baja presión atmosférica. Provoca hipoxemia y los síntomas de hipoxia hipobárica aparecen progresivamente, provocando la incapacidad de las funciones ejecutivas de la tripulación. Los accidentes aéreos que involucran diferentes aeronaves y en diferentes países, debido a la aparición de hipoxia hipobárica en las tripulaciones, han causado cientos de víctimas en la era moderna de la aviación. Para prevenirlos, periódicamente se realizan ejercicios simulados en cámaras hipobáricas con *las tripulaciones con el objetivo de introducirlas en los síntomas de la hipoxia hipobárica de forma segura y controlada y permitirles así volver a actuar durante un incidente aéreo. El intervalo entre ejercicios en cámara hipobárica varía entre países y, aunque no son obligatorios, se sugiere que un intervalo de entre tres y seis años entre ejercicios de hipoxia es apropiado para el mantenimiento efectivo de la seguridad del vuelo con respecto a los síntomas de hipoxia. Sin embargo, es importante tener en cuenta que existe una variabilidad intra e interpersonal en los síntomas de la hipoxia hipobárica.*

Palabras clave: *Hipobarico; hipoxia; ceremonias; hipoxemia; pilotos.*

Hipóxia hipobárica em tripulantes: uma breve revisão sobre etiologia, riscos e exercícios preventivos

RESUMO

A hipóxia hipobárica é oriunda da insuficiência de oxigênio ao aeronavegante devido à baixa pressão atmosférica, ela provoca hipoxemia e os sintomas da hipóxia hipobárica emergem progressivamente, provocando incapacidade das funções executivas do aeronavegante. Acidentes aéreos, de diferentes aeronaves e em diferentes países, devido a instauração da hipóxia hipobárica nos aeronavegantes provocaram centenas de vítimas na era moderna da aviação. Para preveni-los, exercícios simulados em câmaras hipobáricas sao desempenhados periodicamente com os aeronavegantes com o objetivo de apresentá-lo aos sintomas de hipóxia hipobárica de forma segura e controlada e consequentemente permitir sua recordação durante um incidente aéreo. O interstício entre exercícios em câmara hipobárica variam entre países, e embora não sejam obrigatórios, é sugerido que um interstício entre três e seis anos entre os exercícios de hipóxia são apropriados para manutenção efetiva da segurança de voo quanto aos sintomas de hipóxia. Contudo, é importante conscientizar-se que existe variabilidade intra e inter-pessoal dos sintomas de hipóxia hipobárica.

Palabras-chave: *Hipobárica; hipóxia; exercícios; hipoxemia; aeronavegantes.*

1 INTRODUCTION

Accidents involving Learjet flights i. 35 in 1999; ii. 522 Helios Airways flights in 2005; iii. 370 Malaysian Airlines flights in 2014 (Nation *et al.*, 2017); and iv. Senegalair HS-125 flights in 2015 resulted in hundreds of deaths (Table 1). They were caused by exposure to a hypoxic environment not identified by the crew, causing gradual incapacity that culminated in plane crashes (Chiang *et al.*, 2021).

Table 1: Information on flights with accidents due to hypoxia.

	Events			
Identification	N47BA, Learjet 35, SunJet Aviation	Helios 522, Boieng 737-31S, Helios Airways	Malaysian 370, Boeing 77-2H6HR, Malaysia Airlines *	HS-125, Hawker Beechcraft, Senegalair
Date	October 25th, 1999	August 14th, 2005	March 8th, 2014	September 5th, 2015
Flight Origin	United States	Cyprus	Malaysia	Senegal
Occupants	4 passengers 2 crew	115 passengers 6 crew	227 passengers 12 crew	7 total
Fatalities	6 (100.0%)	121 (100.0%)	239 (100.0%)	7 (100.0%)

Identification: call sign, aircraft, manufacter, and operator. * No consensus if the crash was caused by hypoxia.
Source: Wikipedia - The Free Enciclopedia; https://en.wikipedia.org/

Hypoxia is the condition of a reduced level of oxygen that an individual can breathe. Hypobaric or high-altitude hypoxia is a physiological condition in an individual due to reduced barometric pressure. Such a reduction in environmental pressure results in an insufficient amount of oxygen to the body tissues, followed by deleterious effects on human capacity (Blacker; Mchail, 2021), such as short-term memory loss, incoordination, or incapacitation of the individual(Stevenson, 2019). In this context, accidents such as those reported above are likely to occur, causing immeasurable negative consequences to society.

Hypobaric hypoxia prevention adopts a flanking strategy, which includes appropriate use of the aircraft oxygenation system and the identification of hypobaric hypoxia symptoms (Patrão *et al.*, 2013; Woodrow; Webb; Wier, 2011). The successive execution of these instructional exercises allows aircrews to learn, recognize, and understand hypoxic symptoms (Tu *et al.*, 2020). However, human performance and behavior are highly variable, and measuring them in controlled laboratory environments does not necessarily mean the conditions that aircrew routinely endure, especially regarding physical, psychological, and environmental stresses (Shaw; Harrel, 2023), making it important to weigh the conclusions about it. However, discussing and understanding the symptoms of hypobaric hypoxia is essential to maintaining aerospace safety.

2 HYPOBARIC HYPOXIA: DEFINITION, ETIOLOGY, PREVENTION

Hypobaric or high-altitude hypoxia (Bustamante-Sánchez, Delgado-Terán; Clemente-Suárez, 2019) occurs due to a reduction in atmospheric pressure concomitant with an increase in altitude, which implies fewer molecules per unit volume and lower partial pressure of oxygen (Temporal, 2004), resulting in lower partial pressure of alveolar oxygen and arterial blood, a condition called hypoxemia (Bustamante-Sanchéz; Delgado-Terán; Clemente-Suárez, 2019). Hypoxemia impairs brain function (Shaw; Cabre; Gant, 2021) to the point of loss of consciousness and failure (Patrão *et al.*, 2013).

Acute exposure to hypoxia triggers autonomic mechanisms of the cardiovascular system: increases in resting heart rate, cardiac output, and blood pressure; and respiratory: pulmonary hypertension and hyperventilation (Nation *et al.*, 2017) and which are associated with symptoms of hypoxemia: dyspnea, accelerated pulse, visual dysfunction, delirium, euphoria, dyspnea, syncope (Blacker; Mchail, 2021) implying detrimental implications for air operations and flight safety (Bouak *et al.*, 2018).

It is recognized that airmen experience episodes of hypoxia throughout their careers (Artino; Folga; Swan, 2006) with a prevalence close to 63% of cases of depressurization events in airmen of the United States Air Force (Files; Webb; Pilmanis, 2005), with chances of occurrence in a pressurized cabin, at high altitudes, and non-pressurized, at low altitudes (Patrão *et al.*, 2013). These will be part of the professional history of some aircrew throughout their careers (Files; Webb; Pilmanis, 2005; Zhang *et al.*, 2014).

According to Temporal (2004), tolerance to hypobaric hypoxia determines the symptoms of hypoxia triggered by the individual. Of the various symptoms of hypobaric hypoxia; memory impairment (Malle *et al.*, 2013), dizziness, vertigo, tingling, mental confusion, and visual impairment are the most reported (Varis; Parkkola; Leino, 2019). However, the onset and intensity of the symptoms of hypobaric hypoxia depend on some factors, namely: speed of ascent of altitude; flight altitude; ambient temperature; physical activity; age; sex; lifestyle habits; fatigue; smoking; presence of diseases; use of medications; alcohol intake; physical fitness; emotionality; and acclimatization (Alagha *et al.*, 2012; Blacker; Machail, 2021; Bustamante-Sánchez; Delgado-Terán; Clemente-Suárez, 2019; Davis; Johnson; Stepanek, 2008; Singh *et al.*, 2010; Temporal, 2004; Yoneda *et al.*, 2000).

The interval between exposure onset to hypobaric hypoxia and executive function impairment onset is called the time of useful consciousness (Patrão *et al.*, 2013; Temporal, 2004). During this interval, aircrew can take preventive actions against severe symptoms of hypobaric hypoxia: equipping themselves with oxygen masks and reestablishing barometric levels and oxygen supply in the aircraft (Nation *et al.*, 2017). The useful consciousness time allows for predicting the severity of hypobaric hypoxia (Neuhaus; Hinkelbein, 2014; Stevenson, 2019). The average useful time of consciousness at 25,000 feet altitude will occur between three to five minutes (Temporal, 2004).

Prevention of hypobaric hypoxia includes training of aircrew in two areas: i. appropriate use of the aircraft oxygenation system (positive oxygen mask); and ii. timely recognition of hypobaric hypoxia symptoms (Patrão *et al.*, 2013; Woodrow; Webb; Wier, 2011). Regarding the first, aircrew receives instruction on the use of the aircraft oxygen system, including instructions on checking for leaks in hoses and masks, on hermetic sealing of the mask when donning it, and procedures for donning the mask in emergencies (Neuhaus; Hinkelbein, 2014). In addition, the exercises include equipping the aircraft oxygenation system (i.e. donning a positive oxygen mask) and actions to ensure a safe flight altitude for hypobaric hypoxia immediately upon detection of the first symptom (Johnston *et al.*, 2012). Regarding the latter, aircrews execute several tasks while exposed to mimicked conditions of low atmospheric pressure and low oxygen density into a hypobaric chamber. This exercise shows them the decreasing of human capacity (Chiang *et al.*, 2021). Such an exercise is the intentional evocation of hypoxia in a safe and controlled environment, and one of the main exercises in these conditions is the request to identify one's hypoxia symptoms, recording the symptoms and the time of symptom onset (Izraeli *et al.*, 1988).

This exercise methodology more accurately mimics the exposure conditions during flight which allows manipulating the exposure conditions (i.e., exposure altitude, altitude increment/decrement rate, cognitive exercises), to investigate the emergent behavior of the cognitive deficit of communicators (Johnston *et al.*, 2012). It is recognized that the organism's autonomic responses are crucial for the individual's acclimation to hypobaric hypoxia (Nation *et al.*, 2017) and that the symptoms of hypobaric hypoxia experienced in a hypobaric chamber are similar to those eventually experienced on board aircraft (Patrão *et al.*, 2013). Hypobaric chamber exercises provide monitors with the experience of hypoxemia and the emergence of hypobaric hypoxia symptoms, enabling them to recognize their symptoms of hypobaric hypoxia (Davis; Johnson; Stepanek, 2008; Leinonen *et al.*, 2021). Furthermore, repeating the exercises periodically allows pilots to strengthen the memory of their personal hypoxia symptoms (Davis; Johnson; Stepanek, 2008; Leinonen et al., 2021; TU *et al.*, 2020). Of the symptoms of hypobaric hypoxia, likely, the first symptom identified by the individual in an exercise in a hypobaric chamber is the same first symptom (re) cognized in previously performed exercises (Temporal, 2004), it has been knownledge as hypoxia signature (Smith, 2008).

Even so, memory can be wrong. Given this, the International Civil Aviation Organization recommends the adoption of hypoxia prevention programs, including the execution of periodic exercises. However, the frequency of these exercises varies between countries (Figure 2), and it is not mandatory in commercial and general aviation (Kumar *et al.*, 2022), even though military crew members are exposed to more unsafe working conditions due to hypobaric hypoxia compared to civilian crew members (Patrão *et al.*, 2013).

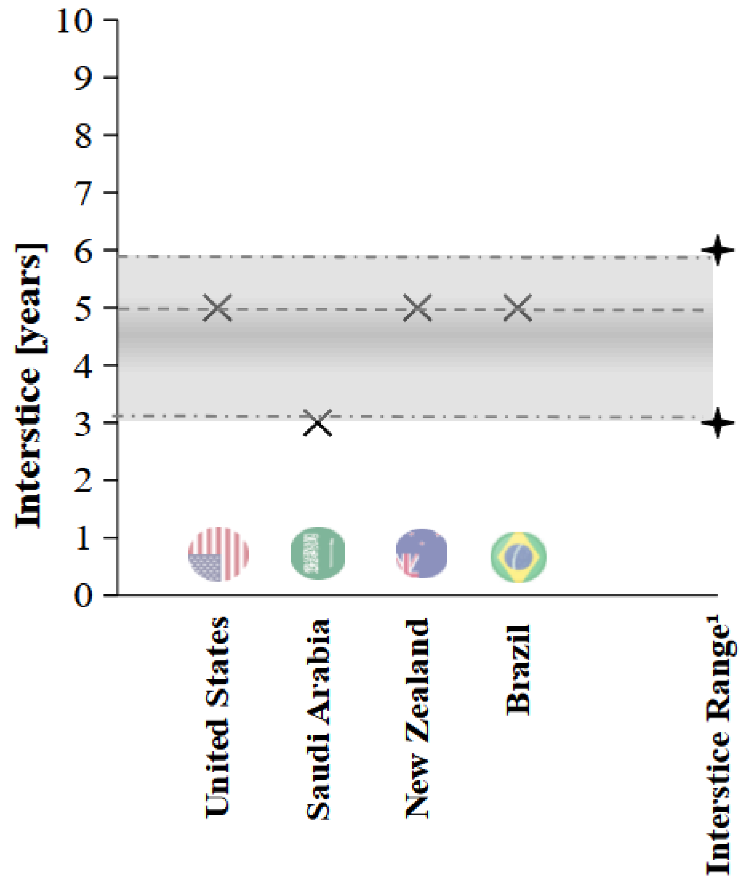

Figure 2: Interstice between hypobaric hypoxia exercise sessions according countries. Source: (BRASIL, 2022; Johnston *et al.*, 2012; Neuhaus; Hinkelbein, 2014)

The interval between hypobaric hypoxia exercises in Saudi Arabia is 3 years, while in Brazil, New Zealand, and the United States, the interval is 5 years (BRASIL, 2022; Johnston *et al.*, 2012; Neuhaus; Hinkelbein, 2014). Although scientific studies comparing hypobaric hypoxia symptoms between hypobaric chamber exercise sessions are incipient, it is proposed that the intervals between exercises should follow intervals between three and six years between sessions (Johnston *et al.*, 2012; Neuhaus; Hinkelbein, 2014).

Comprehension of these symptoms contributes to aerospace safety, and the results presented are concretely applicable in the following contexts:

- pedagogical: instructions in physiological adaptation courses proposed by the Institute of Aerospace Medicine, for example;
- operational: interventions by the military health team that works internally in air squadrons;
- academic: proposing discussions with experts and senior officers to create texts aimed at the needs of the Armed Forces and Auxiliary Forces;
- administrative: especially to encourage the updating of standards, regulations, and legislation on hypobaric hypoxia; and

- technological: constantly feeding and feedback the advancement of technological science, for example, providing information to be used in systems embedded in clothing (i.e., wearable technologies) for physiological monitoring of aviators (Shaw; Harrell, 2023).

3 CONSIDERATIONS

These discussions should be conducted cautiously, especially when aiming to compare the performance of the hypobaric hypoxia exposure methodology with hypoxia in a normobaric environment. Briefly, the mechanism of exposure to hypoxia occurs through the mixture of gases, with no need for variation in environmental pressure (Phillips; HØrning; Funke, 2015). This system is astronomically more economical than the normobaric system, especially in terms of human and structural resources to operate it. These characteristics favor the normobaric system implementation over the hypobaric system, mainly by countries with few economic resources to invest in the Armed Forces.

However, the symptoms of hypoxia observed by the normobaric system do not reach the same standard of recognition presented by the hypobaric system. Cox, Mchail and Blacker (2024) demonstrated through successive surveys of normobaric exposure, half of the sample analyzed (91 subjects) inconsistently reported symptoms of hypoxia different from those presented in the previous sessions. The authors criticize the concept of hypoxia signature, highlighting that experiments conducted in hypobaric environments are poorly designed and analyzed (Cox; Mchail; Blacker, 2024). However, in this case, we do not consider it prudent to extrapolate the results found in one methodology as capable of responding to the phenomenon verified through another methodology (i.e. with versus no gas mixture inhalation). In addition, we assume that the results will be carefully considered given the limitation of mimicking the operational routine of the aircrew in the experimental research design.

In this context, regardless of the physiological results, we may not be able to reliably account for what occurs in the actual hypoxic event (i.e., hypoxia signature; and comparability between hypoxia exposure methodologies), we agree on the need for awareness of the variability of hypoxia symptoms (Cox; Mchail; Blacker, 2024): interpersonal, variety of hypoxia symptoms among individuals; and intrapersonal, possibility of variation between hypoxia events. Associatedly, individuals exposed to hypoxia exercises under controlled conditions must express the validity of this resource to ensure flight safety (Temme; Still; Acromite, 2010). Adding all the factors presented throughout this discussion on hypobaric hypoxia, we consider that periodic exercises in a controlled hypoxic environment should be prioritized in aviation due to their benefits in aerospace safety. Finally, we understand that technological evolution has partially eradicated physiological risks in aerial activity since such risks are inherent to aerial activity under human control. Unfortunately, understanding past air disasters is not and will not be enough to prevent similar disasters in the future. However, we discuss how the presentations in this text address the constant technological advances in this topic.

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