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Controlled Deep Breathing for Rapid Recovery from Hypoxia in Military Pilots and Aircrews

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Abstract: The objective of this research was to determine whether controlled deep breathing (CDB) versus uncontrolled spontaneous breathing (USB) in a normobaric hypoxia environment can increase exposure time in this environmental situation. For this purpose, military pilots and aircrew (n = 167), all of whom were male, underwent a normobaric hypoxia test. They were monitored with a pulse oximeter and subjected to a gradual exposure of up to 18,000 ft (rotary wing) and up to 25,000 ft (fixed wing). Prior to this test, they were briefed and the CDB protocol tested. Subjects using CDB spent more time in hypoxia than those using USB (12':20'' ± 1':28'' vs 9':44'' ± 1':36'', p<.000). For those who exceeded the altitudes of 18,000 ft and 25,000 ft, there were more participants and better percentages were detected, both in a pressurized and non-pressurized cabin, for CDB vs USB (350.76% and 268.88%, respectively). We therefore conclude that CDB can be considered a strategy to induce slower decompression in hypoxic situations in pilots and crew of military aircraft, thus helping to avoid fatal accidents.

Keywords: hypoxia; normobaric hypoxia; deep breath; military pilot; military aircrew; training

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1. Introduction

The first studies on respiratory mechanics were described by Avicenna (980-1037 AD), the Persian medical scholar, who believed that breath-holding promoted the removal of waste from the body, the improvement of arteriosclerosis and the opening of arteries. In one section of his work he described that breath-holding improved respiratory and circulatory function, especially in elderly patients, strengthened the chest muscles, increased lung capacity, decreased abnormal secretions from the respiratory tract and could be used in the treatment of certain pulmonary disorders, such as coughing, as well as in cardiopulmonary rehabilitation [1].

Briefly, the respiratory regulatory system can be divided into control and controlled elements [2]. In the medulla oblongata, there is a neural network that transmits an ideal breathing pattern (reference value) to the bulbospinal promoter neurons, stimulating the respiratory muscles to mobilize the lungs and consequently causing changes in pH, blood pressure and tissue oxygen supply (controlled variables). When there are differences between the reference values and the actual values, the activity of the bulbospinal neurons is modified and the necessary changes in ventilation are produced. Various mechanoreceptors, both in the lungs and in the muscles involved in the motor action of breathing, measure the displacement forces produced by the respiratory neurons and, as a consequence of the interpretation of this information, modify the pattern and level of discharge [3,4].

The literature extensively describes several procedures to assess the behavior of this system, with the respiratory pattern being responsible for informing the intensity of the central inspiratory impulse, through the mean inspiratory flow, and the duration of the components of the respiratory cycle [2,5].

Hypoxia is a state in which the amount of oxygen available in the tissues does not allow adequate homeostasis to be maintained, which may be due to the tissues not having enough oxygen, or to the blood supplying these tissues containing a low level of oxygen (hypoxemia) [6]. Normobaric hypoxia is defined as that type of hypoxia produced by the supply of reduced/insufficient oxygen (lower fraction of inspired oxygen or FiO_2) to the tissues, without a change in ambient pressures (normobaric), causing a decrease in arterial oxygen saturation (SpO_2) [7].

Similarly, we define the concept of time of useful consciousness (TUC) as the period of time between the onset of hypoxia and the inability of the pilot/crew member to correct-ly perform his or her functions. TUC measures the amount of useful time available when experiencing hypoxia prior to loss of consciousness.

The symptoms of hypoxia are very varied and may include mental confusion, lightheadedness, tiredness, flushing, dizziness, shortness of breath, paresthesia, and visual disturbances, among others [8]. Episodes of hypoxia can increase perceived exertion and stress, as well as decrease respiratory muscle function and increase heart rate [9]. Cognitively, it can cause poorer working memory, impaired decision making and impaired oculomotor activity. This entire constellation of signs and symptoms can lead to a decrease in the pilot's performance in flight, leading to potential danger to aviation safety [10–15].

Contributions regarding the effects of hypoxia in the field of aeronautics and specifically in the military have emerged as a necessity [12,16–18], and many of the studies consider how this environmental situation can affect flight safety, mainly due to alterations in psychophysiological variables [19–25].

In the context of altitude training using flight simulation equipment, it has been found that even moderate levels of hypoxia reduce the ability of military pilots to perform a high precision slow flight task [11,26]. During flights below 10,000 ft (3,048 m) in unpressurized cockpits, where hypoxia theoretically has no apparent effect, effects similar to the symptoms described previously also appeared, with statistically significant decreases in SpO_2 detected at altitudes above 5,000 ft. Therefore, the current recommendation is to be aware of the possibility of hypoxia in unpressurized flights at altitudes below 10,000 ft, despite being at a relatively low altitude [27]. Recognition of hypoxia symptoms is therefore necessary to safeguard flight safety [28].

The study by Møller (2010) indicated that the greatest challenge at altitude is associated with a hypoxic environment, and hyperventilation appears as the most critical compensatory response to adapt to hypobaric hypoxia, with hypocapnia being responsible for minimizing the difference between inspired and alveolar oxygen partial pressure [29].

Hypoxia episodes are relatively frequent and potentially very dangerous in military aviation. Consequently, hypoxia training is mandatory for fighter pilots and other flight personnel. Previous evidence-based research on the effects of this training is scarce, and its objective was to validate the effect of normobaric hypoxia training, detecting that this training improved the ability of pilots to recognize the symptoms of acute normobaric hypoxia exposure up to 2.4 years after an initial normobaric hypoxia training session. Considering these results, it is evident that this training is insufficient with respect to the institutional requirements: every 3 years in FINAF (Finnish Air Force), as opposed to the requirement of the North Atlantic Treaty Organization (NATO) Standardization Agree-ment of a 5-year interval between hypoxia training and normobaric hypoxia training [28].

The relative contributions of respiratory rate and tidal volume to the increase in ventilation during acute or prolonged exposure to hypoxia are uncertain, and for this reason the respiratory pattern during hypoxic exposures of minutes, hours or days was analyzed using data from previous studies [30–33]. The conclusion is that tidal volume (amount of air entering the lungs with each normal inspiration) contributed more than frequency to increase ventilation during brief hypoxia [34].

It has also been reported in other studies [30,35,36] that control of slow deep breathing increases oxygen saturation regardless of altitude and, therefore, the state of hypoxia of the subject.

There are infinite ways that hypoxia can occur in the aeronautical world, depending on the altitude and exposure time. The most frequent forms are mild or mild-moderate hypoxia (80%-95%

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SpO_2) through exposure to altitudes between 8,000 ft and 12,000 ft for times ranging between 10-30 minutes, in non-pressurized aircraft [37–40].

Other types of hypoxia are usually due to problems with pressurization systems, failure in oxygen supply systems and structural damage to the aircraft. Obviously, de-pending on the severity of the failure, the exposure can be slow or very pronounced, i.e., the altitude at which it occurs and the exposure time until it is detected will determine the severity of the hypoxia.

There is another type of extremely rapid exposure when decompressions occur, usually due to structural damage, in which exposure to altitude can occur in a few seconds.

Within the aeronautical world there are three principles that must be present in all training programs: prevention, personalization and operability.

Hypoxia exposure time is a critical element in the aeronautical world, as it enables stipulated emergency maneuvers to be carried out more safely. Any measure that allows an increase in the TUC of our flight personnel is considered of great importance. Accord-ingly, the objective of this research was to test whether simulated altitude exposure time increases with voluntary control of respiratory mechanics, in such a way that TUC is ex-tended through voluntary use of ventilatory mechanics.

2. Materials and Methods

2.1. Design and Participants

This study, according to Hernández, Fernández and Baptista (2014), follows an experimental design, as it is a type of study that intentionally manipulated variables (independent), measured outcome variables (dependent), two groups were compared with validated tools and participants were randomly assigned to each group [38].

The participants (n = 167), active military pilots or aircrew, participated in this study voluntarily. All were men, recruited at the time of their mandatory periodic tests for renewal of normobaric hypoxia training at the Aerospace Medicine Instruction Centre (CIMA), part of the Spanish Air Force.

After the initial selection, the nature of the study was explained to the participants, and they were informed that their anonymity would be maintained at all times. The study was conducted in accordance with the principles of the Declaration of Helsinki [39], which define the ethical guidelines for research involving human subjects. The training program used in this research, which is a professional obligation for these participants, was conducted following the rules contained in the Ministerial Order 23/2011, Chapter VII, on Aeromedical Training, as well as NATO Standardization Agreement (STANAG) No. 3114 "Aeromedical Training of Flight Personnel" and STANAG No. 7147. The participants provided written informed consent and throughout the intervention and afterwards, we acted under the provisions of Organic Law 3/2018, of December 5, on the Protection of Personal Data and Guarantee of Digital Rights, regarding the protection of personal data under Spanish legislation.

The selection of the subjects was performed randomly taking into account the conditions described in the table below.

Table 1. Distribution of the sample (n = 167) according to the aircraft flown and type of breathing used during the hypoxia test.

Profile	Subjects	Wing	Group	n
ENH1	Fighter pilots, transport pilots and aircrew	Fixed	A (CDB)	22
			B (USB)	47
EHN2	Helicopter pilots, aircrew, and flight medics	Rotary	C (CDB)	27
			D (USB)	71

CDB = controlled deep breathing; USB = uncontrolled spontaneous breathing.

2.2. Instruments

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For the normobaric hypoxia test, a GO2Altitude® system was used, which obtains hypoxic air through a physical method of oxygen extraction from ambient air by molecular dissociation using membranes. For the psychological tests, we used the manufacturer's integrated software "GO2Altitude Trainer", which provides a battery of cognitive tests to confirm the insidious nature of hypoxia.

2.3. Procedure

The participants performed a normobaric hypoxia test sitting in front of a computer screen to complete a psychological test, where they had to solve situations of hand-eye coordination, memory, and calculation, all monitored with a pulse oximeter placed on the index finger of the non-dominant hand and wearing a helmet and mask from their personal flight equipment. Before starting the test, a demonstration of the psychological test was performed as a means of familiarization.

In the helicopter profile (EHN2), gradual exposure to hypoxia was achieved by designing a flight profile with a simulated maximum altitude of 18,000 ft. In the case of fighter and transport pilots, a profile was designed as above but applying a simulated maximum altitude of 25,000 ft (ENH1).

During the test, the physiological variables of heart rate and oxygen saturation (SpO_2) were recorded, as well as certain cognitive variables according to the tests presented, aimed at simulated flight operations. The simulated altitude and the fraction of inspired oxygen (FiO_2) continuously supplied by the system to simulate altitude were also recorded. The parameters for terminating the training session were measurements below 75% SpO_2, or when the student felt intense feelings of dizziness or discomfort for any reason (overwhelm, feeling of suffocation, flushing, etc.) (Table 2).

Table 2. Protocol for exposure times and altitudes according to the type of aircraft.

EHN1		**EHN2**	
Time (minutes)	Altitude (ft)	Time (minutes)	Altitude (ft)
4	12,000	4	12,000
3	14,000	3	14,000
2	16,000	2	16,000
1	18,000	X	18,000
1	20,000		
X			

ENH1 = aircraft with pressurized cabins; ENH2 = aircraft with non-pressurized cabins; X depends on two criteria: one, that the subject indicates that he/she is not feeling well (dizziness or confusion, generally) or two, that SpO_2 saturation drops below 75%. In both cases, they are then given air enriched to 40% oxygen until they recover, generally 2-4 minutes.

The groups were formed randomly before the start of each hypoxia training session with the personnel attending the aeromedical training. Each of these groups was composed by 4 persons. There were two groups, the CDB group (controlled deep breathing) and the USB group (uncontrolled spontaneous breathing).

The personnel assigned to the CDB group were instructed for 10 minutes before the start of the training to perform controlled full breaths (deep abdominal breathing) at a voluntary frequency according to their own sensations and taking into account that they should start taking these breaths at <85% saturation. The volunteers in the USB group were not given information on CDB and were asked to perform the training using their normal breathing.

2.4. Data Analysis

All analyses were performed with IBM SPSS, version 25. The significance level was defined as $p < 0.05$. The fit of the different variables to the normal distribution was assessed using both graphic procedures and the Shapiro–Wilk test. Finally, parametric testing with Student's *t*-test for related

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samples was undertaken to determine whether the differences were statistically significant were used to visualize these differences (p < 0.05).

The threshold values for Cohen's effect sizes observed in Student's *t*-testing (d) are 0.20 for small effects, 0.50 for moderate effects and 0.80 for large effects [40].

3. Results

Each group, distributed both by aircraft type and by breathing type, showed a normal distribution.

The results obtained for the total duration of the hypoxia test for the fixed-wing and rotary-wing samples, i.e., for pressurized and non-pressurized cabins, are presented below. It can be seen that, regardless of the type of cabin, the subjects in the CDB group, i.e., those who performed the controlled deep breathing technique, obtained significantly better results.

Table 3. Descriptive statistics (M ± SD), contrast (Student's *t*-test for independent samples) and effect size for the groups: fixed wing with Uncontrolled Breathing (n = 47), fixed wing with Controlled Breathing (n = 21), rotary wing with Uncontrolled Breathing (n = 71) and rotary wing with Controlled Breathing (n = 71) (n = 26).

	Fixed Wing				**Rotary Wing**			
	USB	CDB	*p*	*d*	USB	CDB	*p*	*d*
Time (mm:ss)	9:44 ± 1:36	12:20 ± 1:28	.000	1.730	9:34 ± 1:47	14:22 ± 4:31	.000	1.407

CDB = controlled deep breathing; USB = uncontrolled spontaneous breathing; mm = minutes; ss = seconds.

The following table shows the results of those participants who exceeded 9, 10 or 11 minutes of exposure to hypoxia, respectively. In all cases in which CDB was performed, better results were detected, with statistically significant differences compared to USB.

Table 4. Descriptive statistics (M ± SD), contrast and effect size, independent of aircraft, for the different exposure times greater than 9 minutes with Uncontrolled Spontaneous Breathing and Controlled Deep Breathing.

Time (mm:ss)	**Wing**	**Uncontrolled Breathing**	**Controlled Breathing**	***p***	***d***
> 9′	Fixed and Rotary	(n = 81) 10:30 ± 1:11	(n = 47) 13:28 ± 3:47	.000	1.114
>10′	Fixed and Rotary	(n = 52) 11:05 ± 1:05	(n = 45) 13:38 ± 3:36	.000	0.962
>11′	Fixed	(n = 10) 11:45 ± 00:32	(n = 18) 12:41 ± 1:16	.026	1.236

Significance value p< .05; M = mean; SD = standard deviation; mm = minutes; ss = seconds.

Finally, the percentages of participants who reached the maximum altitude (18,000 ft, for fixed and rotary wing, and 25,000 ft, fixed wing) are presented. Also shown is the time spent at this altitude, observing that when comparing both groups, CDB had a much higher success rate (156% for altitude above 18,000 ft and 230.59% for altitudes above 25,000 ft) than USB.

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Table 5. Percentages of subjects reaching altitude and maintained exposure times according to aircraft type and breathing.

Altitude	Wing	Uncontrolled Breathing		Controlled Breathing		Difference
		Subjects (%)	Exposure time (mm:ss)	Subjects (%)	Exposure Time (mm:ss)	%
>18,000 (ft)	Fixed and Rotary	44	1:05	100	3:48	350.76
>25,000 (ft)	Fixed	8.47	00:45	38.29	02:01	268.88

mm = minutes; ss = seconds; ft = feets.

4. Discussion

The work of Møller (2010) indicated that hyperventilation in hypoxic environments was beneficial for improving tolerance. In our case, it was observed that deeper and slower ventilation allowed the subjects to remain in hypoxic conditions longer and with a lower oxygen depletion, achieving differences in the percentage of time above 200% compared to those who used uncontrolled or spontaneous breathing.

Regarding studies that have explored the effects of respiratory pattern changes during hypoxic exposures [7–10], Nepal et al. (2010) examined two populations living at different altitudes (2,800 m and 3,760 m) and compared the difference in hematocrit, finding that those who performed a slow deep breathing exercise increased SaO_2 independent of altitude. These results coincide with those of our research, although Nepal et al. (2010) do not report whether these differences are statistically significant, as they only provide a graph in which a better result is observed with deep breathing, while our statistical analysis does show statistically significant differences and also confirms a large effect size (> .80) and at much higher altitudes (18,000 ft = 5,486 m and 25,000 ft = 7,620 m). The work of Bernardi et al. (2001 a) evaluated the influence of the same breathing patterns as our study during an altitude-induced exposure (5,000 m, in a hypobaric chamber) although they only used 19 subjects: 9 performed spontaneous breathing and 10 yoga trainees performed slow diaphragmatic thoracic breathing (~5 breaths/min). Similar to our research, in those who practiced controlled breathing, the $\%SaO_2$ decreased significantly less ($p < .05$) than in those who performed spontaneous breathing (8% vs 14%, respectively), concluding that well-performed slow yogic breathing maintains better blood oxygenation and reduces sympathetic activation during altitude-induced hypoxia.

Bernardi et al. (2001 b), although with a sample of only 15 subjects, carried out a study in isocapnic hypoxia with breathing rates of 6 or 15 breaths/minute, terminating the test at a saturation of 70% SaO_2 (75% in our case), concluding, as in our study, that the benefits of slow breathing (6 breaths/minute) in hypoxic conditions reduce the chemoreflex response to both hypoxia and hypercapnia.

Bernardi et al. (2006) also evaluated 11 elite climbers because they believed that a very high ventilatory response to hypoxia was required to reach extreme altitude without oxygen. To explore this, they measured oxygen saturation and hypoxic ventilatory response at rest at sea level and at 5,200 m after 15 days of altitude acclimatization. Their results showed that the most successful climbers had lower responses to hypoxia (i.e., smaller decreases in saturation) during acclimatization at 5,200 m, concluding, along the same lines as the results of our research, that greater ventilatory efficiency in response to hypoxia could improve ventilatory reserve and make sustainable ventilation possible in a hypoxic situation similar to that of the pilots and aircrew we studied.

Regarding respiratory frequency and hypoxia, the main focus of this research, one of the first studies published in this area was that of Bender et al. (1987) who aimed to determine the relative

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contribution of respiratory frequency and tidal volume to the increase in ventilation during acute or prolonged exposure to hypoxia. To do this, they examined respiratory pattern changes during hypoxic exposures of different durations (although we will only compare those lasting a few minutes, in their case 3-7 minutes, because of the similarity to our research). Based on the results obtained, they concluded that tidal volume contributed more than frequency to the increase in ventilation during brief hypoxia. Thus, to a certain extent, this work, although distant in time, coincides with ours, given that in both studies it is not the increase in respiratory frequency that allows greater tolerance to hypoxic conditions, but rather a greater tidal volume, which is possible to achieve through slow deep breaths, as has been done by the subjects in the controlled breathing group in our study, and in others in which it has been found that tidal volume in brief exposures to hypoxia contributes more than frequency to increase ventilation [29]. In this same sense, modifying the breathing pattern so that it is performed slowly and deeply increases oxygen saturation independent of the altitude and the hypoxia condition of the subject [26,31].

Leinonen et al. (2021) were concerned about the frequency of pilot training under hypoxia, as in our case, warning of the low level of recall (2.4 years) that pilots and crew members have with respect to the time elapsed between trainings (3-5 years)[24] To this, should be added the contributions of recent research on the potential effects that physical training has shown to attempt to minimize the effects of in-flight hypoxia [40–42].

Strengths and Limitations of This Study

One of the main strengths of this study is the sample size, which with 167 participants is one of the largest in the literature. It also distinguishes between those who work in pressurized and non-pressurized cabins and shows the tolerance to hypoxia according to the type of breathing performed, as the simulated altitude is increased during training in normobaric hypoxia.

Among the limitations, and also future lines of research, we should point out that once the benefits of controlled deep breathing to minimize episodes of hypoxia in flight are known, and in order to further examine the mechanisms of action, it would be very useful to have continuous reading of respiratory volumes, flows, and frequencies during hypoxia exposure, i.e., more precise measuring instruments are needed to assess respiratory variables throughout the training, and also to relate them to the data from regional cerebral oximetry. Ultimately, the aim is to be able to determine which ventilatory patterns are most effective and adaptive for each situation: controlled deep inspiration with final contraction of abdominal and thoracic musculature; rapid expiration; controlled inspiration and expiration; rapid inspiration and controlled expiration, etc. These techniques could offer greater assistance in the environmental conditions under which we conducted this research as well as in others with similar characteristics in terms of duration and/or altitude associated with flight risks.

5. Conclusions

The general conclusion drawn from this study is that CDB is a breathing technique that allows slower saturation decreases in hypoxic situations and faster recoveries. Moreover, CDB can be considered a strategy to prevent rapid desaturation in hypoxic conditions in pilots and aircrew of military aircraft, which could help to avoid fatal accidents. This training strategy, which allows the respiratory volume to be adjusted according to the situation, has a clear preventive character by minimizing the adverse effects of the psychophysiological symptoms of hypoxia (hyperventilation, tachycardia, dyspnea, etc.), improving the psychophysiological response with a slower and more prolonged desaturation, and finally, providing a subjective feeling of control of the stress-related symptoms that may occur.

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Abbreviations

The following abbreviations are used in this manuscript:

CDB	Controlled Deep Breathing
USB	Uncontrolled Spontaneous Breathing
FiO_2	Fraction of Inspired Oxygen
SpO_2	Arterial Oxygen Saturation
TUC	Time of Useful Consciousness
FINAF	Finnish Air Force
NATO	North Atlantic Treaty Organization
CIMA	Aerospace Medicine Instruction Centre
STANAG	NATO Standardization Agreement
ENH1	Aircraft with pressurized cabins
ENH2	Aircraft with non-pressurized cabins
mm	Minutes
ss	Seconds
M	Mean
SD	Standard deviation
Ft	Feets

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