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Flight Physiology in Unpressurized Aircraft Cabins

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Dedicatory

Is my deep wish to thank and dedicate this work to all my family, especially to my parents, who always supported me and pushed me to move forward, and make all I am and achieved today possible and real.

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"Our doubts are traitors and cause us to miss the good we oft might win by fearing to attempt."

William Shakespeare

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Abstract

Light aviation pilots are exposed to many different environmental situations due to the non-pressurized and non-acclimatized aircraft cabin. Some of those variations can push the human body to some limits, which associated with psychological factors may culminate in incidents or even fatalities. Actually, a literature review on this theme suggests that a significant part of the incidents and fatalities, within the light aviation that uses non-pressurized aircraft cabins, are related to the human factor. This analysis might bring up a concealed but significant and worrying phenomenon in terms of flight safety: changes of pilot performance in the amendment of psychological and physiological parameters, concerning to different stress levels and to pressure variations during the various flight stages, respectively. This may be a concerning situation due to the disparity of human body reaction between different pilots to the same flight conditions. Nature, both in terms of environmental factors, as pressure and temperature, or in human physiological and psychological behaviour, during the different flight phases, is unpredictable. Therefore, it is very difficult to establish safety boundaries.

This study general objective is to analyse the influence of flight environmental conditions and pilots psychophysiological parameters on task performance, during different flight situations, considering some of his everyday habits. To this end, a statistical analysis of a survey, regarding specific questions about the need for pilot’s attention monitoring systems, was made, and, in parallel, a portable and ergonomic monitoring system was built. This system equipment records cerebral oximetry, to study the hypoxia phenomenon and its importance, electrocardiography (ECG), and electroencephalography (EEG), in order to establish a correlation between the influence of mental workload and other physiological parameters during different flight stages.

The specific purpose of this study is to define physiological limits for each pilot, through simulation tests contemplating different flight scenarios, in order to create an on board alert system to prevent possible incidents.

With this research is also intended to suggest that a potential restriction on pilots licensing legislation for light aviation, within physiological limits definitions, would be a positive contribution to a safer flight environment.

Keywords:

Light Aviation; Unpressurized and Unacclimatized Cabins; Physiological and Psychological Parameters; Safety Boundaries; Flight Conditions; Monitoring Systems.

Resumo

Os pilotos de aviação ligeira estão expostos a diferentes situações ambientais devido às cabines não pressurizadas e não climatizadas. Algumas dessas variações podem levar o corpo humano aos seus limites, que associados a fatores psicológicos podem culminar em incidentes ou até mesmo fatalidades. Na verdade, uma revisão da literatura sobre o tema sugere que uma parte significativa dos incidentes e acidentes neste tipo de aviação, estão relacionados com o fator humano. Esta análise pode revelar um fenómeno oculto, mas significativo e preocupante em termos de segurança de voo: as mudanças de desempenho dos pilotos aquando da alteração de parâmetros psicológicos e fisiológicos, referentes a diferentes níveis de *stress* e variações de pressão durante as diferentes fases do voo, respetivamente. Esta pode ser uma situação preocupante devido à disparidade da reação do corpo humano entre pilotos diferentes, para as mesmas condições de voo. A natureza, quer em termos de fatores ambientais, como a pressão e a temperatura, quer a nível de comportamento fisiológico e psicológico humano, durante as diferentes fases de voo, é imprevisível. Portanto, torna-se muito difícil estabelecer limites de segurança.

O objetivo geral deste trabalho consiste em analisar a influência das condições ambientais de voo e dos parâmetros psicofisiológicos do piloto sobre o desempenho de tarefas, durante situações de voo diferentes, considerando alguns dos seus hábitos quotidianos. Para este fim, foi feita uma análise estatística a um inquérito sobre questões específicas referentes à necessidade de sistemas de monitorização da atenção do piloto, e, em paralelo, foi construído um sistema portátil e ergonómico de monitorização. Este permite registar a oximetria cerebral, para estudar o fenómeno da hipoxia e a sua importância, ECG e EEG, a fim de se estabelecer uma correlação entre a influência da carga de trabalho mental e outros parâmetros fisiológicos, durante as diferentes fases de voo.

O objetivo específico deste estudo é definir os limites fisiológicos de cada piloto, por meio de testes de simulação de voo, contemplando cenários diferentes, a fim de criar um sistema de alerta a bordo para evitar possíveis incidentes ou acidentes.

Com esta investigação pretende-se também sugerir que uma eventual restrição na legislação referente ao licenciamento de pilotos de aviação ligeira, dentro das definições dos limites fisiológicos, seria uma contribuição positiva para um ambiente de voo mais seguro.

Palavras – Chave:

Aviação ligeira; Cabines não pressurizadas e não climatizadas; Parâmetros fisiológicos e psicológicos; Limites de segurança; Condições de voo; Sistema de monitorização.

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List of Acronyms

ACT	Altitude Chamber Training
ATA	Atmospheres Absolute
bpm	Beats Per Minute
CP	Cognitive Potential
ECG	Electrocardiography
EEG	Electroencephalography
EP	Evoked Potentials
FAR	Federal Aviation Regulations
ft	Feet
FL	Flight Level
GPS	Global Positioning System
hPa	Hectopascal
HR	Heart Rate
ICAO	International Civil Aviation Organization
JAR-OPS	Joint Aviation Requirement – Operation Performance Standard
MHR	Maximum Heart Rate
mmHg	Millimetres of Mercury
MSL	Mean Sea Level
O_2	Oxygen
rSO2	Regional Oxygen Saturation
SpO2	Haemoglobin Saturation
TUC	Time Useful of Consciousness
USA	United States of America

1. Introduction

1.1 Motivation

Flying is a growing reality that, although being used mostly for fast passenger and cargo transportation, is also increasingly requested for leisure purposes only, by a very heterogeneous pool of pilots. This may be a concerning situation due to the disparity of human body reaction between different pilots to the same flight conditions.

The light aviation and glider pilots are exposed to many different environmental situations due to the non-pressurized and non-acclimatized aircraft cabin. Some of those variations can push the human body to some limits, which associated with psychological factors may culminate in incidents or even fatalities. Nature, both in terms of environmental factors, as pressure, temperature and humidity, or in human physiological and psychological behaviour during the different flight phases, is unpredictable. Therefore, it is very difficult to establish safety boundaries.

With increasing altitude, pressure decreases and, consequently, also reduces the oxygen partial pressure. The oxygen partial pressure decrease may cause the Hypoxia phenomenon, which can compromise the pilot's performance and, consequently, the flight safety. Once, each individual both in terms of physiological and psychological characteristics is unique, a standard safe altitude is difficult to establish, because what generally isn't considered a concerning altitude, may be lethal for a pilot who has some minor, but crucial in this situation, lung or heart problems. In low altitude flights, generally, hypoxia will not represent such a major factor to the well trained pilot but plays an important role in the sports or amateur pilot who is not as well trained in such conditions.

Flight safety is a crucial topic in the aviation industry; it's a subject that constantly has something to improve, and that will never be completely optimized, because there will always be the unpredictable human and nature factor. This study comes in sequence of a previous work, developed by Leandro Rocha [1], in 2011, related to the measurement of pilots' physiological parameters, as brain oximetry, in the study of the hypoxia phenomenon, during ultralight flights. It's a project that came with the challenge of optimizing Rocha's work by extending the monitored physiological parameters to the ECG and EEG and relates them with pilot's everyday habits and the flight environmental conditions, in order to understand how those factors may be relevant in the pilots' flight performance.

As mentioned before, human factors, as awareness of flight physiology, have an essential role in flight safety. However, an initial review of the international legislation showed that there are no requirements for ground training in flight physiology, for light aviation and glider pilots. The law only establishes limit altitudes to which supplemental oxygen is required.

Educating individuals about their own symptoms within a supervised ground location would provide essential information. A prior experience in altitude chamber training (ACT) would allow the hypoxia experience to be less novel and may improve recognition of its symptoms and each individual limits.

There are many unexplored situations related to the light aviation that deserves our best concern, so in order to improve safety for everyone this dissertation intends to answer to some of the international legislation flaws.

1.2 Object and Objectives

The object of the current dissertation is the flight physiology and psychology, the light aviation pilots' performance, training experiences, training requirements and perceptions about altitude sicknesses, and flight safety.

The main objective may be divided into three sub-objectives. The first is to analyse a survey, implemented to all Portuguese pilot community, in order to understand pilot training experiences and perceptions, about training requirements and altitude sicknesses, in flight safety.

The second sub-objective is to obtain synchronized data between physiological parameters (brain oximetry; ECG; EEG) and flight parameters (GPS coordinates; interior temperature and humidity; G load). In order to obtain and conciliate all this data, a small, light and ergonomic monitoring system was built. The first phase of this sub-objective is to apply this monitoring system in simulated flight scenarios, as hypobaric chamber and flight simulators. The second phase is to test pilots in real flight environmental conditions, in order to, in a third phase, compare both tests data to establish individual physiological limits. The fourth phase consists in adapting the monitoring system to recognize pilots' physiological limits and alert them to them. Once crossed, the physiological boundaries of each pilot can comprise his flight performance and, consequently, the flight safety. Whereby, having on board a system that would alert the pilot for that danger would give him time to descend for a secure altitude or use a supplemental oxygen system, if implemented on board. Having time to take these decisions is crucial in the prevention of incidents and/or accidents that may endanger the pilot live and the integrity of the aircraft, making this alert system an asset for unpressurized aircraft pilots' safety.

The last sub-objective is a consequence of its predecessors and implies a set of founded recommendations, in order to change the flaws in the Portuguese legislation, related to this subject.

1.3 Dissertation Structure

The development of this dissertation started with a literature review of the human psychophysiological factors and how altitude and unpredictable flight and environmental conditions can influence the pilots' performance and, consequently, compromise the Flight Safety. Then, an exhaustive research on the Aeronautical Legislation was made in order to understand the existing laws regarding the influence of the mentioned factors on unpressurized aircrafts. Simultaneously, a statistical analysis, based on an online survey released in 2011, was made in order to understand the pilots' perspectives and perceptions about these factors.

The first chapter is the study introduction, which is divided into three sub-chapters, the motivation, the object and objective, and the structure of the dissertation, respectively.

The second chapter corresponds to the state of art and contains the studied psychophysiological factors, as well as its monitorization methods, and its effects on human physiology, and it also includes an aeronautical legislation review, regarding this subject.

In the third chapter is possible to observe the online survey statistical analysis, and the experimental results, obtained from the hypobaric chamber and real flight tests.

The fourth chapter addresses the discussion of the survey results and the experimental work analysis.

The fifth (and last) chapter contemplates the dissertation synthesis, the final considerations and the prospects for future work in this matter.

2. State of Art

2.1 Introduction

The current chapter addresses the general State of Art where, firstly, a literature review of the flight physiology, the different psycho-physiological parameters, their influence on pilot's performance and, consequently, on the flight safety, was made. Different methods and techniques for psychophysiological parameters monitoring, were also explored in the current chapter.

A legislation review, inherent to the laws concerning the study object of this dissertation, i.e., those regarding the requirements and training requirements for flight safety, was also included in the current chapter.

2.2 Flight Physiology

Since the beginning of its existence, that man aspires to conquer the skies. There are many myths and legends about the existence of beings possessing divine powers, exploring the skies like birds. Many were the attempts to achieve this dream, most failed, but never in vain. Many were those who believed it was possible, annihilating any impossibility of realizing the dream, because after all *If a man thinks one thing, another will makes it reality,* Júlio Verne. Today, flying is a reality and may even say a banality, is an experience that is considerably within reach of all, being used primarily for fast and safe transportation but also as a leisure activity. It is in this last point that the concern lies, in other words, to optimize safety within the aviation leisure for who flies and who is on the ground.

Flying is an activity of enormous responsibility, it is necessary to consider a wide range of factors which, when not respected, can lead to a set of irreversible situations with large moral and economic damage.

Over the years, several studies have been conducted based on different types of flight situations/conditions that might influence the pilot performance during the flight, which may endanger their own, and other's lives, and why a monitorization would be important.

2.2.1 Hypoxia Phenomenon

The atmosphere can be defined as a thin layer of odourless, colourless and tasteless gases attached to the earth by gravity [2]. At sea level, the pressure is approximately 760 mmHg, and oxygen concentration in the atmosphere, to about 39,370.08 feet (ft) of altitude (the beginning of the stratosphere), is constant, about 20.95%. The physiological effects derived from the inspired gases are determined from the gas partial pressure, whose value can be calculated by multiplying the air pressure (absolute value 1 ATA = 760 mmHg) by the fraction of gas existing in a given altitude; for example, the partial pressure at sea level is 0.21 ATA.

The atmospheric pressure is influenced by altitude, latitude and temperature. For an altitude of 18,000 ft the atmospheric pressure is about half, compared to the same at sea level; however, despite this decrease with altitude, the oxygen concentration remains up to 39,370.08 ft.

According to Boyle's Law, the volume occupied by the same gaseous mass, at the same temperature, is inversely proportional to the pressures that it supports. Thus, it is possible to understand the effects of altitude on the human body cavity organs, including the ears, sinuses, stomach and intestines. Given the rise of an aircraft, there is a gas expansion consequent on falling barometric pressure, and in the fall, the reverse situation occurs.

According to Dalton's law, in a gas mixture, the pressure of each gas component is independent of the others, and the total pressure is the result of the sum of the partial pressure of each component of the mixture.

The main constraint of high altitude, lies the fact that, although the percentage of oxygen remains constant up to the stratosphere, the hypoxia phenomenon occurs during the fall of atmospheric pressure and the resulting decrease in the partial pressure of oxygen in ambient air and alveolar air, due to the reduction of gas exchange.

The appearance and intensity of the symptoms of hypoxia depend on factors like the speed of ascent, the absolute altitude flight, the duration of exposure to low atmospheric pressure, temperature and individual characteristics such as disease, everyday habits, physical fitness, acclimatization and emotion. Symptoms such as fatigue, drowsiness, dizziness, headache, and euphoria can occur, as also as, when exposed to this phenomenon, vision and hearing become impaired, the reasoning is faulty and may result in loss of memory and slow and uncoordinated reactions [2], [3].

To identify the phenomenon, the most widely used procedure consists in monitoring the pulse oximetry, which in turn can be peripheral or cerebral, the latter being addressed in this work. The cerebral oxygenation (and somatic) is a non-invasive method capable of allowing the simultaneous monitoring of oxygen in brain tissue and the body surface. The regional oxygen saturation (rSO2) is a "vital sign" that reflects the critical balance between supply and consumption of oxygen, in other words, informs, which is the available oxygen, after the tissues have taken what they need [4].

Several studies on the hypoxia phenomenon and possible warning equipment have been made over the years, with the respective knowledge and technologies continuously evolve, thus enabling the realization of this work.

In 1967, the FAA [5] carried out a study which the main objective was the analysis of the student pilots performance regarding their past 24 hours habits, as hours of sleep, medication and alcohol ingestion. To do that, the pilots were submitted to two questionnaires, one before the flight and another one after, where in the last one they were asked to describe the procedures, manoeuvres and emotions realized and felt, respectively, during the flight. Also, during the flight, each pilot was fitted with different sensors for different data acquisition. With this study, was possible to observe that the student pilots performance can be affected by the combination of altitude and stress.

In 1994, Richardson [6] has patented a device called Hypoxia Aviation Monitor, which was the incorporation of oximetry equipment in the pilot's headphones. The oximeter sensor was implemented in the headphone, in a way to fit in the back of the ear, and would be connected through the wires of the same which, in turn, were linked to a monitor in the control panel of the aircraft, allowing the monitoring of oxygen levels during the flight.

Nesthus *et al.* [7] in 1997 published a study on the effects of mild hypoxia on flights up to 12,500 ft without using supplemental oxygen. With their work, the authors intended to evaluate the physiological and subjective pilot's responses, against a backdrop of cross-country flight, where, for such, submitted a sample of ten pilots to simulator tests during three days, about two hours a day. During the tests the subjects of the simulation sample breathed oxygen mixtures simulating sea level, between 8,000 ft and 12,500 ft. In conclusion, the authors found that there is an enormous variation in levels of performance and tolerance among individuals, due to exposure to low altitudes in the laboratory when confronted with simple and complex tasks. Also in this year, the FAA [8] performed a study involving twenty private pilots, where ten constituted the test group that breathed different oxygen mixtures, equivalent to different altitudes, and the other ten constituted the control group that only breathed compressed air simulating, approximately, sea level altitudes. This study results showed that, significantly, more procedural errors were committed by the test group pilots, for simulated altitudes of 10,000 ft, specially, during the descent and approach phases, then for the control group. So, was possible to observe that hypoxia is a condition that can develop itself below 12,500 ft, depending on each individual tolerance to oxygen deprivation. Also, was possible to conclude that performing descent and approach manoeuvres, while breathing an oxygen mixture corresponding to a 10,000 ft altitude, could be generally unsafe with potential dangerous outcomes.

Cable [9] in 2003 carried out a survey of all instances, with military aircraft, between 1990 and 2001 in Australia, which listed the hypoxia as a possible cause. These cases were analysed individually taking into account the type of aircraft, the number of persons on board, the number of persons on board who have experienced symptoms of hypoxia, the existence of fatalities and the altitude at which the occurrence happened and what was the probable cause. During the study period about 27 reports of hypoxia, involving 29 crews, were declared, with only two cases involved loss of consciousness, one of which resulted in fatality. With his research, Cable could conclude that most of the events associated with hypoxia were found for altitudes below 19,000 ft and confirm the importance and relevance of information and training of the passengers and crew, respectively, for this type of situation.

In 2009, Wilson *et al.* [10:175] performed a study on the cerebral effects of ascent to high altitudes, since "The brain is the most oxygen-dependent organ in the body and many pathophysiological processes either cause or result in an interruption to its oxygen supply". In their study, the authors intended to cover altitude sports fans communities and people living in elevated areas, in particular, as the continuous exposure to the hypoxia phenomenon may or may not contribute to the onset or aggravation of certain diseases. With its research, the authors concluded that the controlled study of brain lesions is quite volatile because of the many variables that exist and differ from individual to individual. However, they found that for a short exposure to the hypoxia phenomenon, the effects were irreversible, thus providing an ethical, clean, repeatable, controlled and prospective model of brain responses. Furthermore, in conclusion, the authors found that the brain damage caused by hypoxia have different mechanisms in the cause of, for example, traumatic brain injuries.

Simmons *et al.* [11] in 2010 published a study whose objective was to compare the sensitivity and equivalent results, between two equal pulse oximeters, one that would be implemented on the forehead and another on the finger, in the detection of states of hypoxia. The data suggested a satisfactory agreement of results between both implementations of pulse oximeters, but the sensor that was implemented on the forehead, was dramatically more sensitive to changes in SpO2 (haemoglobin saturation) induced by altitude. However, when compared with the clinical standard, although the forehead implemented oximeter was also sensitive to the oxygen decline in haemoglobin saturation and precise, significant changes would be required in order to eliminate flaws in the measurements, due to the movement of the structure.

In short, clearly, the hypoxia phenomenon is the most studied constraint of flight, at the level of oxygen deprivation, trough the oximetry during flight, that may be associated to various symptoms, such as can be seen in Table 1.

Table 1: Hypoxia Symptoms [1].

Amnesia
Stunning
Increased self-confidence
Shortness of breath
Muscular incoordination
Decreased ability of perception of color
Decreased visual capacity
Decreased reaction time
Discernment committed
Speech uncoordinated
Headache
Numbness (inaction in the face a certain task / problem)
Euphoria
Lack of concentration
Slow movements
Changes in personality
Obsession with a certain task
Loss of self-criticism
Tips of toes and fingers, nails and lips blue
Poor reasoning
Feeling short of breath
Tingling in fingers and toes
Feeling hot and cold
Somnolence
Dizziness
Tremors in the skin
Tunnel vision

Furthermore, considering the symptoms and the physiological limits caused by the exposure to hypoxia, Time Useful of Consciousness (TUC) is defined as the time elapsed between the loss of supplemental oxygen and the failure of performance. TUC is a parameter that can be determined experimentally in hypobaric chamber (simulated low pressure), trough psychomotor tests, being that with "Physical activity, even moderate, the TUC reduces up to 50%" [2:252]. Table 2 shows the observed variation of the TUC with altitude, where it can be seen that it decreases as altitude increases, and, depending on the activity of the individual at the time of oxygen failure, physical condition, their quotidian habits, among others, the window of opportunity, i.e., TUC, may vary over any other individual. Smoking is one of the factors that dramatically reduce the tolerance to lack of oxygen, it can reduce the individual's capacity in about 3,000 to 6,000 ft. TUC for an average individual smoker, at 15,000 ft, would be between 10 to 20 minutes or so, while for a non-smoker it would be about 30 minutes or more [12]. In situations of rapid depressurization, the TUC is reduced by half [13].

Table 2: Time Useful of Consciousness [13].

Altitude (FL)	Altitude (ft)	Time Useful of Consciousness
150	15,000	30 minutes, or more
180	18,000	20 to 30 minutes
220	22,000	5 to 10 minutes
250	25,000	3 to 5 minutes
280	28,000	2,5 to 3 minutes
300	30,000	1 to 3 minutes
350	35,000	30 to 60 seconds
400	40,000	15 to 20 seconds
450	45,000	9 to 15 seconds
500, or above	50,000	6 to 9 seconds

Fatigue is a very common symptom and frequently associated with pilot error. Some of the effects of fatigue include degradation of attention and concentration, impaired coordination, and decreased ability to communicate. These factors seriously influence the susceptibility to hypoxia and the ability to make effective decisions. Factors, such as stress and prolonged performance of cognitive work, result in mental fatigue [14].

2.2.2 Cardiac and Respiratory Rates

The heart is a muscle that has electrical activity from the change of the relative amount of sodium ions, present inside and outside of the myocardial cells, being this the cause of different cyclical variation of the same ion concentrations in the peripheral areas of the body. This electrical activity is responsible for the sequential contraction of the several heart chambers, allowing the passage of blood from the atria to the ventricles and from these to the large vessels, thus creating a circulation through various organs and body systems. To measure this variation refers to the electrical performance of an ECG that is essentially the same external registration of cardiac electrical activity, which flows through the biological tissues, causing electrical potentials. The signal is recorded from electrodes placed in various parts of the body, including limbs and chest wall. The combination of both electrodes, placed at different body sites, makes possible to obtain leads that correspond to different forms of analysis throughout the cardiac cycle, the electrical stimulus. From the analysis of an ECG is possible to draw conclusions about the state of the heart, such as [15]:

- Change in heart rhythm (arrhythmias);
- Changes in conduction (block following the electrical stimulation);
- Effects of certain drugs.

The heart has a limit, and that is where the maximum heart rate (MHR) concept comes, which is the greater frequency of heart beats that can be reached at the maximum effort for a given individual. This is a concept whose value varies with the level of aerobic fitness of the individual, can decrease when gains in cardiovascular fitness and vice versa. With the physical exercise, an individual may experience a decrease of about 7% of the MHR [16], [17].

Respiration is a physiological process whose main goal is to exchange oxygen and carbon dioxide between the atmosphere and body tissues. The cellular activity uses the oxygen from inhaled air and produces carbon dioxide which, in turn, is expelled during exhalation. The amount of oxygen required by the body is determined by the level of activity or metabolism of various tissues, and an increase in metabolic activity leads to increased speed and depth of inhalation and exhalation processes. A healthy individual at rest has a respiratory rate of about 12 cycles per minute. During periods of intense mental effort and stress, a phenomenon known as hyperventilation can occur. The most convenient respiratory indices, referring to the pilots, are the measurements of respiratory rate, flow and volume of air, and the values of oxygen and carbon dioxide in the body. The measurement of respiratory rate is probably the most relevant and useful index, because it is easier to obtain and serves as an indicator of emotional state, level of stress, arousal and mental effort [18].

The high burden of brain activity that may be subject to a pilot during a flight, is a factor that can interfere with heart and respiratory rate, in particular, the appearance of spontaneous fluctuations, derived from reactions caused by various mechanisms / psychophysiological factors, such as emotions, concentration, decision making, level of responsibility, performing tasks and physical capacity during the entire flight, emphasizing phases as take-off and landing [18], [19]

2.2.3 Cerebral Load Activity

The brain is one of the most complex and mysterious organs in the human body; it has about 100 billion neurons, each connected by more than 10,000 synaptic connections, communicating among themselves by protoplasmic fibres, that are responsible for the conduction of electrical impulses, known as action potentials, to various parts of the brain and the rest of the body, so that they can be received by specific cells. "The brain is not the independent counsel agent, residing in splendid and lofty superiority in our skulls. Rather, it is a part of an extended system reaching out to permeate, influence, and be influenced by, every corner, and extremity of your body "[20:2].

The EEG is an examination to detect any electrical activity of the brain, where several electrodes are placed on the scalp over multiple areas of the brain in order to highlight and record patterns of electrical activity and any anomalies. The electrodes are connected by cables to a signal amplifier and recording equipment that converts electrical signals into a series of wavy lines, which are then printed on graph paper [15].

During the operation of an aircraft, the pilot has to collect, filter and process information with high speed, which increases neural activity and the level of arousal, which are more evident and important for phases of flight of more complex manoeuvres such as approach, landing and take-off [17].

The logic in the use of physiological parameters for measuring the burden of brain activity is based on the concept of "activation" or "excitement," a state of alertness on the part of the body at the time of increased activity in the nervous system. Duffy [21:17] in 1962 described "(...) the level of activation of the organism to the extent of release of potential energy, stored in the tissues of the organism as this is shown in the activity or response", as also as that "(...) it would be possible to define the activation of the arousal which occurs in the absence of physical exertion". In 1965, Welford [22:2] suggested that any job applicant or effort "(...) which is in some way challenging (...)" increased the excitement.

In 1987, Kraaier *et al.* [23] performed an experimental study which evaluated the quantitative changes in the EEG of normal subjects subjected to a low-pressure environment, simulated in a hypobaric chamber. With their research, the authors found that there was a significant increase in slow brain activity during the predominance of hypobaric hypoxia.

Mann and Sterman [24:1], in 1995, published a review about quantitative studies of the human EEG during signal detection, flight simulation and actual flight performance tasks based on the basic animal perspective research on the neurophysiological and functional correlations of relevant rhythmic patterns. The compilation, allowed the authors to observe distinct EEG frequency changes into the psychomotor behaviour signal processing and intrinsic attention modulation, during complex performance. With their acknowledgements, the authors concluded that the EEG can provide a valid and objective parameter for mental effort, yet, additionally, may also reveal "(…) task-related cognitive resource allocation, task mastery and task overload".

Another method of brain load monitorization is the Evoked Potentials (EP), that consists in the study of the sensory pathway, in other words, the transmission circuits of sensitivity along the structures of the central nervous system, whether deep sensitivity (present on the hands and feet), hearing, or vision. Thus we have, respectively, somatosensory, auditory and visual evoked potentials.

While EEG is the recording of spontaneous electrical activity at a cortical level, EP depends on a stimulus to elicit the response. The method for obtaining EP consists of applying a set of stimuli and recording of electrical responses to it along a particular nervous path. The stimuli may be visual, auditory or somatic [25].

The EP differs from EEG in two aspects: first, while the EEG is a continuous signal from the cortical activity, the EP is the brain's response to a repetitive stimulus applied over a nervous way; second, while the EEG is a signal present in the entire scalp, with amplitudes of about

10 to 200 mV, the EP amplitudes are in the order of hundredths of a microvolt to 5 mV and require precise positioning of the electrodes and processing of multiple stimuli, in order to extract them from the EEG (background activity). The stimuli are applied repeatedly, preferably at random intervals, and averaged records obtained. This technique is known as signal averaging and was designed by Dawson in 1954 [26] and subsequently adapted for processing by digital computer [27].

The long latency evoked potentials, especially the cognitive potential (CP), are directly influenced by the patient's motivation, their level of attention and previous experience. Routinely, the cognitive potential can be obtained with hearing stimuli and registered with two different stimuli in the same mode, but with different physical characteristics. One of the stimuli is frequent while the other is only occasional, being both processed in random intervals. The equipment separately records the evoked brain activity caused by the frequent stimuli (ignored by the patient) and the rare stimuli (one to which the patient is aware).

Franco [28], in 2001, realized an experiment with twenty five healthy and normal individuals submitted to different hearing stimulus, nominally, a frequent and a rare stimuli, where he observed that with the CP method was possible to diagnose some dysfunctions during the realization of simple tasks, while compared with standard parameters.

The EP methods have a growing applicability in studies about flight safeness, nominally, in the measurement of pilot's attention and concentration during different flight phases, when exposed to various psychological and environmental factors [29].

2.3 Legislation

Human factors, as awareness of flight physiology, have an essential role in flight safety [30]. Although, there are no requirements, at the international legislation, for additional education on hypoxia symptoms, for unpressurized aircraft cabin pilots.

Providing supervised ground training and education, as ACT, would allow the individuals to better recognize their own symptoms. A prior experience in ACT would also increase the recognition of hypoxia and critical reaction time [31].

In order to understand which are the imposed rules, that protect the flight safety in matters of at which flight altitude should be required supplemental oxygen, a review on aviation legislations was made.

The following sub-chapters are a summary of International, North American, European and Portuguese legislations, within the above-mentioned topic. Those are given by ICAO Annex 6, FAR 91.211, JAR-OPS 1.775 and *Decreto-lei* nº 289/2003, respectively.

2.3.1 International Legislation, ICAO Annex 6, Part I [32]

A flight to be operated at flight altitudes at which the atmospheric pressure in personnel compartments will be less than 700 hPa (13,000 ft) shall not be commenced unless sufficient stored breathing oxygen is carried to supply:

a) All crew members and 10 per cent of the passengers for any period in excess of 30 minutes that the pressure in compartments occupied by them will be between 700 hPa and 620 hPa (10,000 ft);

b) The crew and passengers for any period that the atmospheric pressure in compartments occupied by them will be less than 620 hPa.

2.3.2 United States of America (USA) Legislation, FAR 91.211 [33]

At cabin pressure altitudes above 12,500 ft (MSL) up to, and including, 14,000 ft (MSL), unless the required minimum flight crew is provided with and uses supplemental oxygen for that part of the flight at those altitudes that is of more than 30 minutes duration.

2.3.3 European Legislation, JAR-OPS 1.775 [34]

An operator shall not operate a non-pressurized aeroplane at altitudes above 10,000 ft unless supplemental oxygen equipment, capable of storing and dispensing the oxygen supplies required, is provided.

2.3.4 Portuguese Legislation, Decreto-lei nº 289/2003 [35]

Portuguese legislation is based on, above mentioned, European legislation JAR-OPS that, in short, says that is the pilot in command responsibility to ensure that members of the flight crew, in the performance of their duties, use supplemental oxygen continuously whenever the aircraft exceeds 10,000 ft, for a period longer than thirty minutes.

2.4 Conclusion

Leisure flights in unpressurized aircraft cabins, nominally, ultralight and glider aircrafts are a growing activity in Portugal. There are many symptoms related to different flight conditions that can compromise the pilot performance. Indeed, each person reacts differently to the same stimulus.

Both legislations, just recommend/demand restrictions related to the use of supplemental oxygen when standard flight altitudes are crossed, neglecting the fact that each person has unique characteristics and that unpressurized aircraft pilots have a significant vulnerability to environmental and flight conditions. In short, according to the international legislation, flying conditions, as altitude, only become dangerous for those who fly above 10,000 ft, for longer than 30 minutes, with no supplemental oxygen.

3. Case of Study

3.1 Introduction

The nature, both in terms of environment conditions, including weather, or the physiological level of the pilot during the flight, is unpredictable and, therefore, one of the most difficult to define, that is, establish safety boundaries. As already mentioned, in the first chapter of the current study, the objective of this research is to analyse the influence of flight conditions, as altitude, on the performance of the pilot, taking into account some physiological parameters and some of the pilot everyday habits.

3.2 Survey

As mentioned in the beginning of the current chapter, a statistical analysis was made based on a survey (Annex 1) presented by Rocha [1]. Permission was obtained from the corresponding author to use the obtained data from April until November of 2011.

The main objective of this survey was to collect information from a heterogeneous group of pilots regarding their hypoxia experiences, their hypoxia training backgrounds and their perceptions about its relevancy, and their impressions about the need for an ACT. This study also intended to analyse how a physiological monitoring system would be considered relevant, in pilot's perspective, to increase flight safety.

3.2.1 Pilot Demographics

The general database included 117 pilots, 115 male and 2 female, with a mean age of 42 years. Most respondents were non-smokers (83%) and exercised assiduously (54%). Their flight background activities were several, being general aviation (84%), significantly, the dominant category. Generally, each pilot reported various levels of certification as light aviation (70%), commercial (27%), airline (21%) and flight instructor (13%). Among the light aviation licensed group were the private (64%), the ultralight (48%) and the glider pilots (14%), where the majority had the three certifications in common (Figure 1).

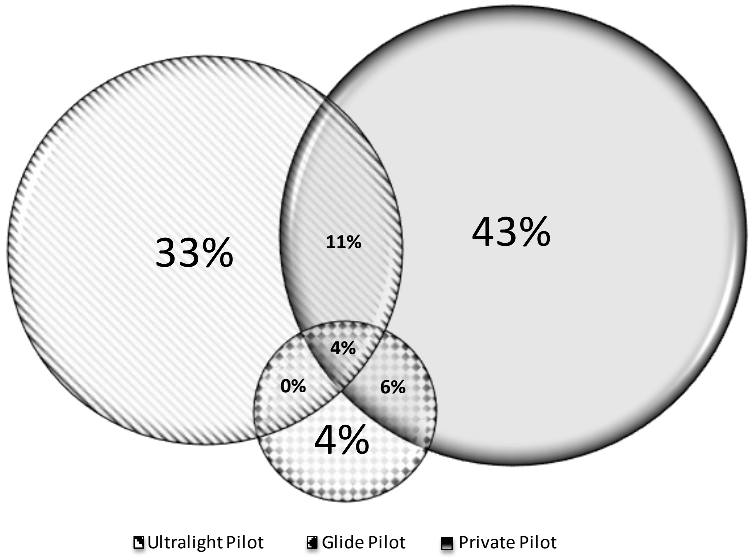
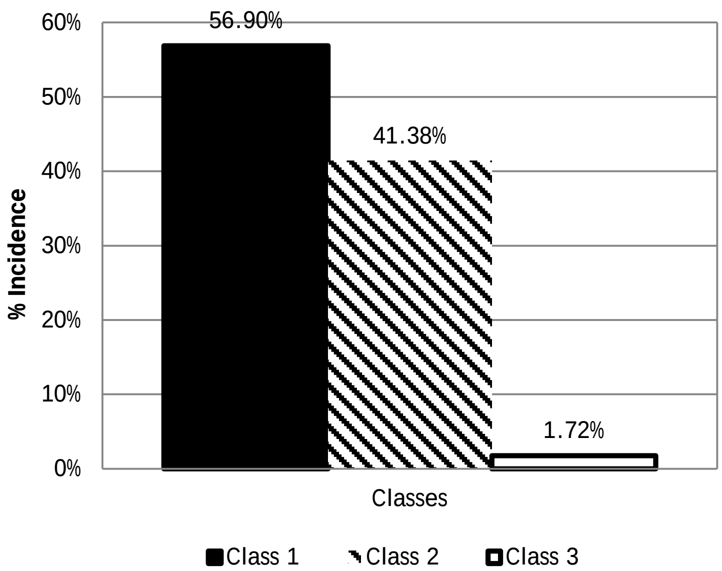


Figure 1: Diagram illustrating the percentages of licensed pilots in three light aviation categories. The intersections translate the percentages of pilots who have certifications in common.

Of the pilots included, 56.90% had class 1 medical license (for Airline and Commercial Pilot functions or license privileges in multiple crews as a crew member), 41.38% had class 2 medical license (for student pilot, private pilot, flight engineer or navigator functions) and 1.72% had class 3 medical license (for air-traffic control activities), (Graphic 1).



Graphic 1: Percentage of pilots for each medical class license.

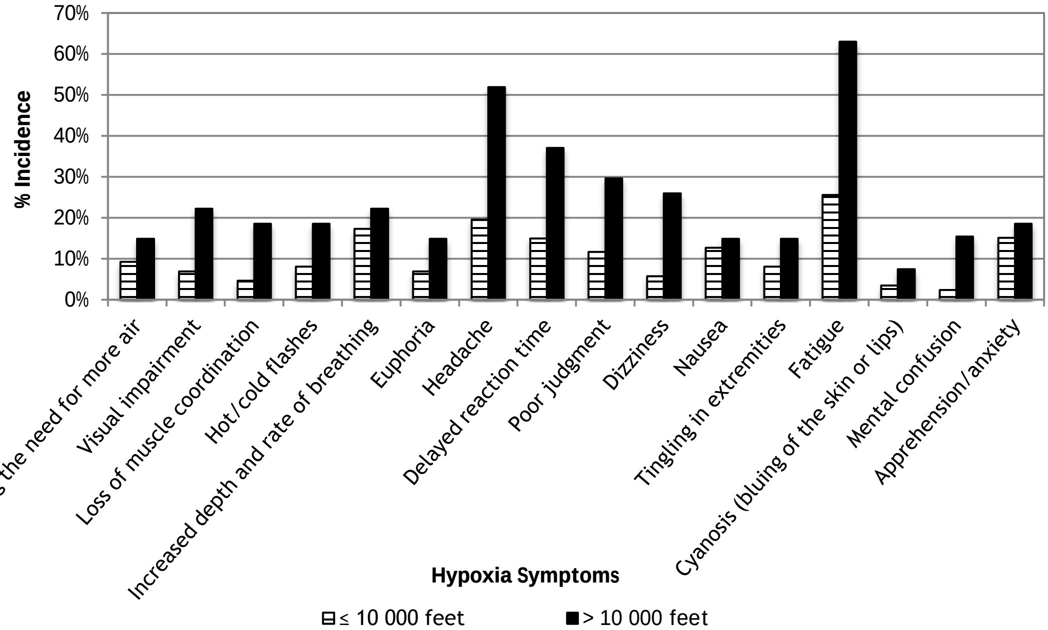
3.2.2 Pilot Training Experiences

Of all the included pilots, 74% alluded that most of the performed flights, in the six months preceding the survey, were accomplished in unpressurized aircraft cabins, at a maximum ceiling of 10,000 ft. Further, 53% of the pilots reported having training on hypoxia fundamentals, where 32% have light aviation license, and 33% usually fly below 10,000 ft. About 61% took a basic introductory course on hypoxia fundamentals, without ACT; 26% took an initial ACT, where only one pilot frequently had hypobaric chamber training; and 13% took a recurrent course on hypoxia fundamentals without ACT. Additionally, of the pilots who had attended hypoxia training, 92% agreed and strongly agreed that the course was informative and addressed topics such as the effects, symptoms of hypoxia and other possible high-altitude sickness. 46% of the pilots considered formation/training in the hypoxia useful.

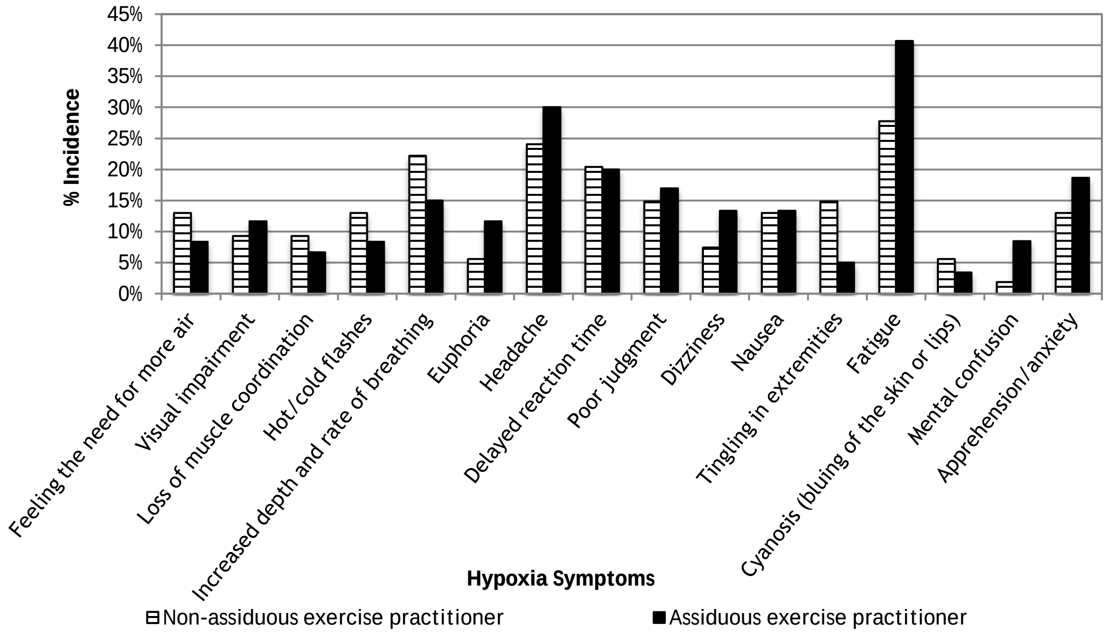
3.2.3 Pilot In-flight Experiences with Hypoxia

There were two items assessed to the occurrence of hypoxia. Most pilots (95%) stated that had never experienced it and 59% believed that at the environmental and altitude conditions, that they usually fly, there are scarce chances of hypoxia.

Hypoxia may reveal itself under several symptoms and when questioned about them, a portion of the pilots (54%), where 70% fly below 10,000 ft, reported having experienced at least one of the addressed symptoms (Graphics 2 and 3).



Graphic 2: Percentage of pilots who have felt each one of the various hypoxia symptoms. The sample of pilots was divided into those who usually fly below 10,000 ft and those who fly above it.



Graphic 3: Percentage of pilots who have felt each one of the various hypoxia symptoms. The sample of pilots was divided into those who usually exercise and those who don't.

3.2.4 Pilot Attitudes on Hypoxia Training Requirements

Some of the inquest items were related to the pilot's perception concerning specific hypoxia training requirements. A five level likert scale was adopted to evaluate the agreement with some hypoxia training requirements. In the statement that pilots should make a basic introductory course related to the hypoxia phenomenon (not including ACT), 81% of the respondents agreed or strongly agreed. Furthermore, 48% of the sample population agreed or strongly agreed that all pilots should make recurrent hypoxia training without ACT. When questioned if all pilots should make an initial ACT, about 58% of the respondents agreed or strongly agreed. Faced with the sufficiency of the current aeronautical regulations, specifically those regarding the education and training for hypoxia situations (i.e., not requiring ACT), 39% of the respondents disagreed or strongly disagreed.

When questioned about which pilots should do an ACT, 63% of the respondents agreed that it should depend on the flying altitude average, whereas 56% agreed that it should depend on the pilot license rating.

Taking into account only those pilots who usually fly below 10,000 ft (75% of the respondents), 81% believed that pilots should receive a basic introductory hypoxia course (without ACT) and 50% agreed with an initial ACT. On the other hand, 38% disagreed or strongly disagreed with the sufficiency of the actual aeronautical regulations and 60% defended that the type of pilot license should be decisive in ACT.

When specific hypoxia training needs were assessed for fourteen types of pilot certification, the majority of the pilots perceived the need for an introductory hypoxia course (without ACT) as necessary for ultralight pilots (60%), glider (52%) and private (51%). The type of certification was also relevant for initial ACT with pilots referring an important need for training for commercial (46%), flight instructor (42%) and pilots who commonly fly in pressurized aircraft cabins (42%) than for amateur/sport (32%) certification levels. The respondents also found important a periodic ACT for airline pilots (51%), pilots who commonly fly in pressurized aircraft cabins (39%) and flight instructors (25%), regardless the type/class of certification.

For those who both have light aviation license and usually fly below 10,000 ft (61%), a significant part considered relevant an introductory hypoxia course (not including ACT) for ultralight (66%), glider (51%) and private (42%). However, 42% of these pilots defended an initial ACT for recreational flight certification types.

The last two items of the survey aimed to probe the respondents in order to see how far they found relevant the use of a monitoring system, in real time, and whether they would be receptive to its use if it is proven to contribute to flight safety. Hereupon, 75% of the pilots found it useful and 92% affirmed they would use it. Among light aviation pilots these percentages were even more expressive, being 83% and 94%, respectively.

3.3 Experimental Work

As previously mentioned, the current work comes in sequence of a previous study [1] where a monitoring system for brain oximetry was tested in ultralight pilots, during real flight conditions. The adopted equipment, for brain oximetry, was the same used in [1], i.e., the Nonin Medical Inc. Model 7600 Regional Oximetry System (Figure 2).

Figure 2: Nonin Medical Inc. Model 7600 Regional Oximeter System, 2 Channel Configuration [36].

This equipment has two precision sensors, regardless of skin type, features or blemishes. With an intuitive, easy-to-operate user interface, it offers Bluetooth® wireless technology connectivity, in order to allow a posterior access to the stored data. Model 7600 is durable, has a rugged design withstands rough treatment, which makes it usable until 12,000 ft, in a range between -5ºC and +40ºC [37]. Each sensor of the Nonin Medical Inc. (Model 700) was placed on the frontal region of each cerebral lobe (Figure 3).

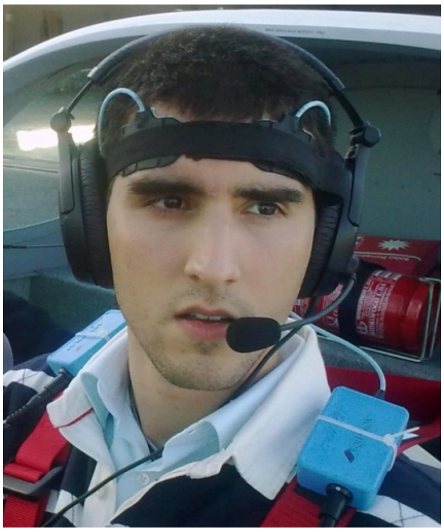


Figure 3: Nonin Medical Inc. (Model 700)
equipment configuration.

For the heart rate (HR) measurement, the Garmin Forerunner 305 (Figure 4) was the used equipment. This equipment has a wireless heart rate monitor with a GPS receiver that comfortably wraps around the pilot's chest and measures his HR.

Figure 4: Garmin Forerunner 305 [38].

In the current work, in parallel with the cerebral oximeter and the HR equipment, was also assembled a flight data recorder, to record the flight parameters, as geographical coordinates, attitude, ground speed, gravitational force (G-force), temperature, humidity and pressure inside the aircraft cabin. Both equipment were synchronized in the same time scale, to allow the comparison between physiological and flight data.

All this equipment combination was projected, assembled and submitted to several experimental tests, in order to assure the pilot's comfort and safety.

The experimental tests were performed by two male individuals with different characteristics (Table 3), where the individual 1 was an inexperienced pilot, with a few hours of real flight and that had never realized the hypobaric chamber training. The individual 2 was a much older pilot, with many hours of real flight, as a flight instructor and pilot, and with many hypobaric chamber trainings.

Table 3: Characteristics of the tested pilots.

Individual	Gender	Age	Physical Exercise	Smoker	HR (bpm) (mean value at rest)	rSO2 (%) (mean value at rest)
1	Male	25	Rare	No	93	78
2	Male	60	Assiduously	No	70	62

In all the following graphics, only one lobe, regarding the cerebral oximetry, was observed, once the obtained values for each one was, approximately, equal.

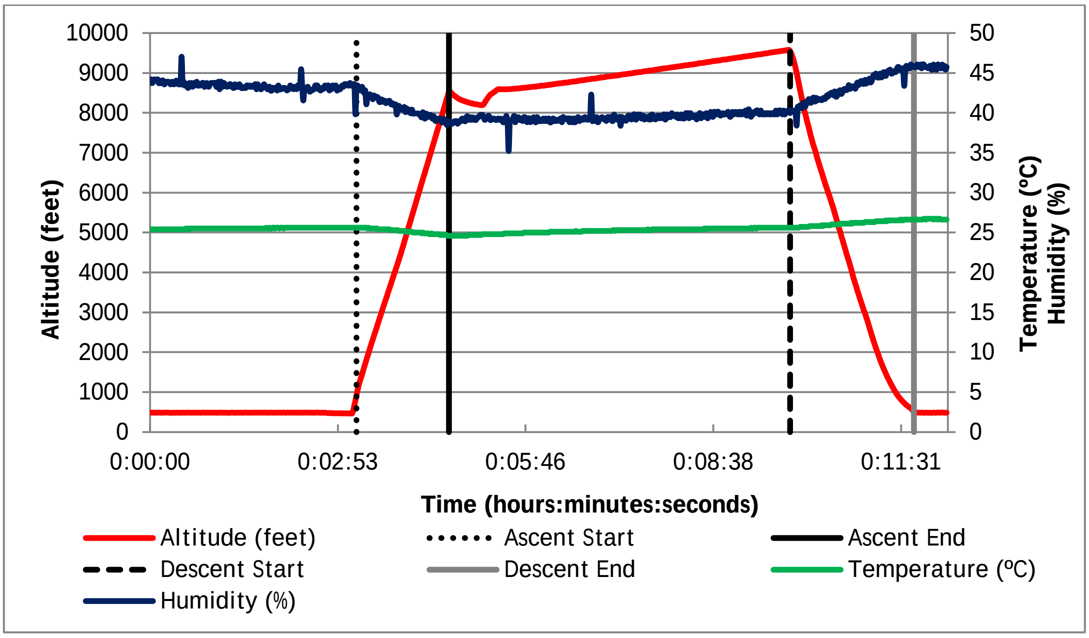
3.3.1 Hypobaric Chamber Tests

The hypobaric chamber test took place in the *Centro de Medicina Aeronáutica* of Portuguese Air Force (Figure 5), in the Lumiar military base, in Lisbon, Portugal; it had duration of, approximately, 12 minutes with a maximum simulated altitude of 9,577.9 ft above sea level.

The cerebral oximetry, pressure, temperature and humidity values were measured during the entire simulation.

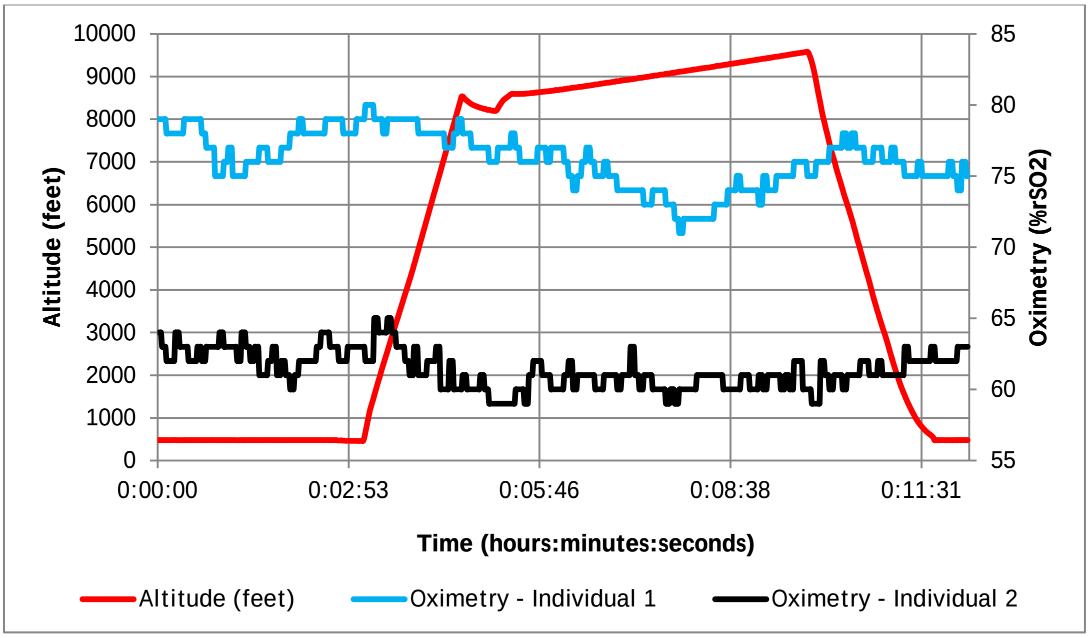
Figure 5: Hypobaric Chamber of *Centro de Medicina Aeronáutica* of the Portuguese Air Force.

In Graphic 4 may be seen that the test began with a climb of, approximately, 6,078.2 ft per minute, up to 9,577.9 ft, and after reaching the maximum altitude, both individuals remained in the simulated environment during 5 minutes, after which they started descending. The minimum temperature was, approximately, 25 degrees Celsius (°C) and occurred by the end of the ascent, approximately, at the maximum altitude. The humidity started at, approximately, 43% and by the end of the test was around 46%.



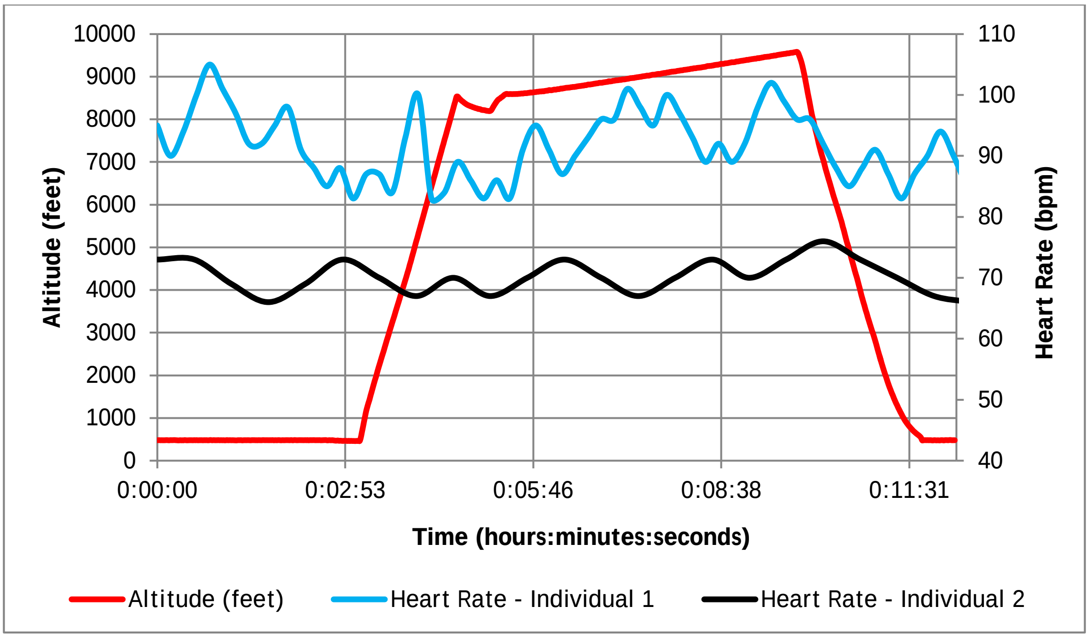
Graphic 4: Temperature, humidity and altitude variation during the hypobaric chamber test.

In Graphic 5 may be seen that at the beginning of the test the regional oxygen saturation (rSO2) mean value was 77.5% and 62.5%, for individual 1 and individual 2, respectively, which corresponded to the maximum absolute value recorded during the entire test. From that moment, the rSO2 mean value decreased almost continuously, for the individual 1, until around 00:07:52 (hours:minutes:seconds) when it reached the absolute minimum of 71%, that was approximately two minutes before the moment where the maximum altitude was reached, about 9,577.9 ft. For the individual 1, the rSO2 mean value, for the entire flight, was 76.2%, with a standard deviation of 1.96 bpm. It may also be observed that the rSO2 value, for individual 2, is practically the same during the entire test, with a mean value of 61.4% and a standard deviation of 1.33 bpm.



Graphic 5: rSO2 and altitude variation during the hypobaric chamber test.

In Graphic 6 may be seen that at the beginning of the test, the HR mean value was 93 bpm and 70.2 bpm, for individual 1 and individual 2, respectively. From that moment, the HR value oscillates expressively, for the individual 1, until the end of the test. The HR mean value, for individual 1, was 90.3 bpm with a standard deviation of 5.3 bpm. It may also be observed that for individual 2 the HR is practically the same during the entire test, with a mean value of 70.2 bpm and a standard deviation of 2.7 bpm.



Graphic 6: HR and altitude variation during the hypobaric chamber test.

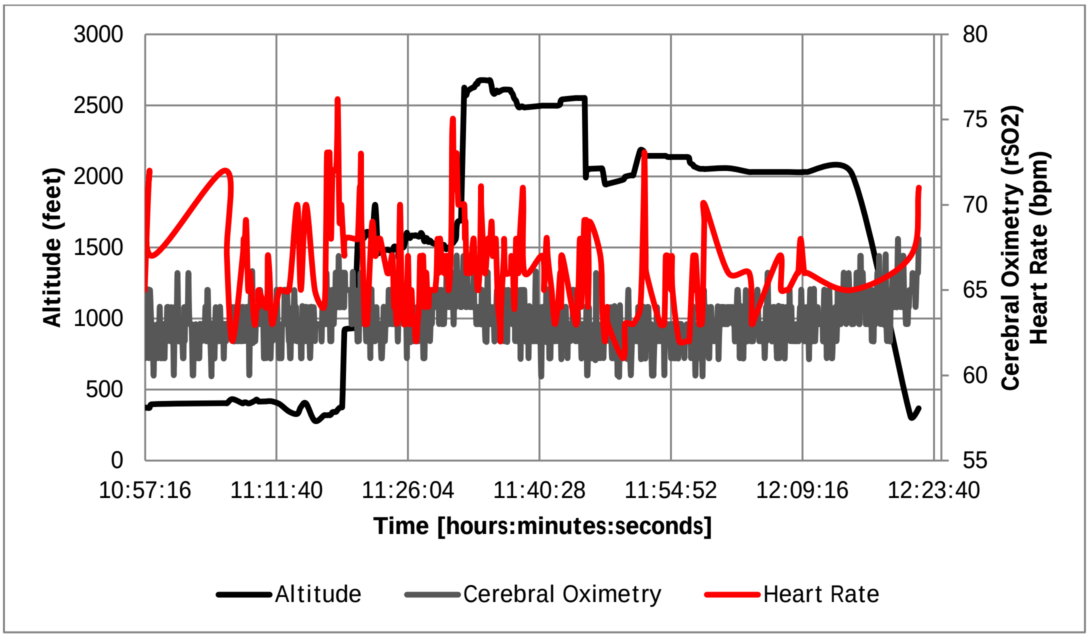
3.3.2 Real Flight Tests

Four real flight tests were realized (Table 4), where three of them were performed by the individual 2, and only one by the individual 1. All the three flights performed by individual 2, took place in Tires airfield, in Cascais, Portugal, while the performed flight by individual 1 took place in Viseu airfield, also in Portugal.

Table 4: Characteristics of the performed flights.

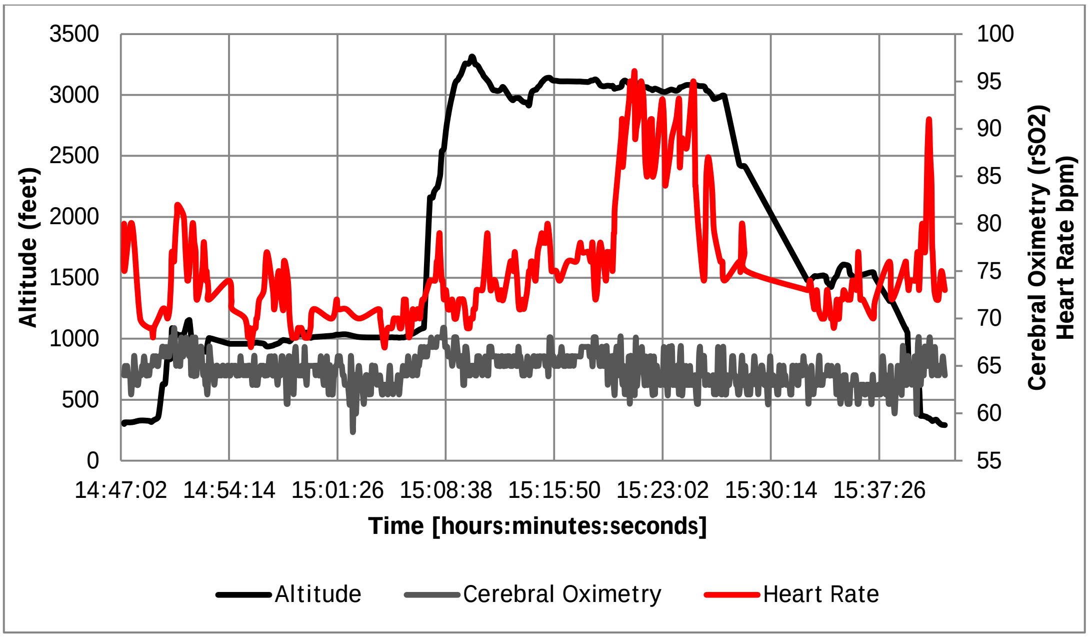
Real Flight Tests	Individual	Maximum Altitude (ft)	Duration (hours:minutes:seconds)	Observations
1	2	2,677	02:25:44	Calm Wind; Mild Flight
2	2	3,313	00:54:32	Strong Wind; Turbulent Flight
3	2	6,433	02:56:04	Calm Wind; Mild Flight
4	1	8,394	00:51:32	Calm Wind; Flight with some intense manoeuvres

In Graphic 7 may be seen that the first test (1) had a maximum altitude of 2,677 ft above sea level and had duration of, approximately, one hour and five minutes. At the beginning of the test, the regional oxygen saturation (rSO2) mean value was 63.5%, and after the first ascent, at 11:19:04, it reached the 67%, which corresponded to the maximum absolute value recorded during the entire test. From that moment, the rSO2 mean value was approximately the same during the entire test, with a mean value of 63.3% and a standard deviation of 1.33. It may also be seen that there were three expressive peaks in the HR value; one by the middle of the first ascent (11:18:22), another by the moment the aircraft starts to climb to the maximum altitude (11:30:59), and the last at 11:51:57, where they reached 76 bpm, 76 bpm and 73 bpm, respectivley. Besides those, the HR values don't oscillate much, having a mean value of 66 bpm with a standard deviation of 2.6 bpm.



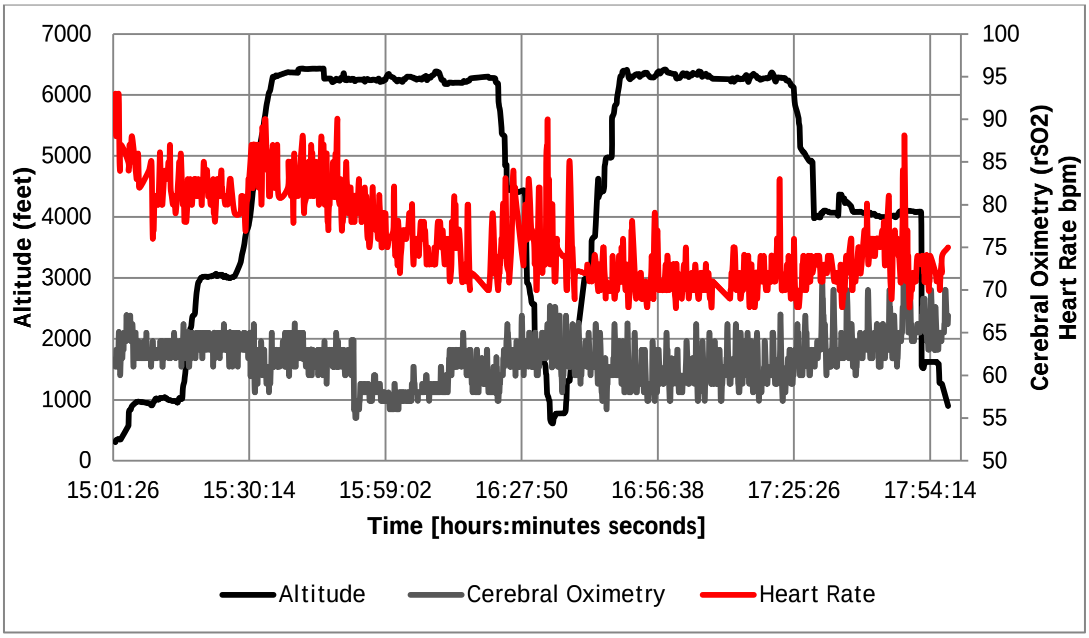
Graphic 7: Altitude, rSO2 and HR variation during the real flight, test 1.

In Graphic 8 may be seen that the second test (2) had a maximum altitude of 3,313 ft above sea level and had duration of, approximately, fifty five minutes. At the beginning of the test the regional oxygen saturation (rSO2) mean value was 64.5%, by the moment after the first climb (14:50:24), at 1,030 ft, the rSO2 reached a relative maximum value of 69%, and by the end of the second climb (15:09:13), at 3,256 ft, it reaches its maximum absolute value recorded during the entire test, 70%. Except the mentioned moments, the rSO2 mean value was practically the same during the entire test, with a mean value of 64.5% and a standard deviation of 1.66. It may also be seen that there were a couple of consecutive expressive HR peaks by the preceding moment (15:20:54) to the aircraft's first descent, at 3,073 ft, where they reached 95 bpm; and by the landing moment (15:40:45), where it reached the 91 bpm. The mean value, during the entire test, was 75 bpm with a standard deviation of 6.2 bpm. Therefore, the HR values variation is much more expressive when compared with the obtained data from test 1.



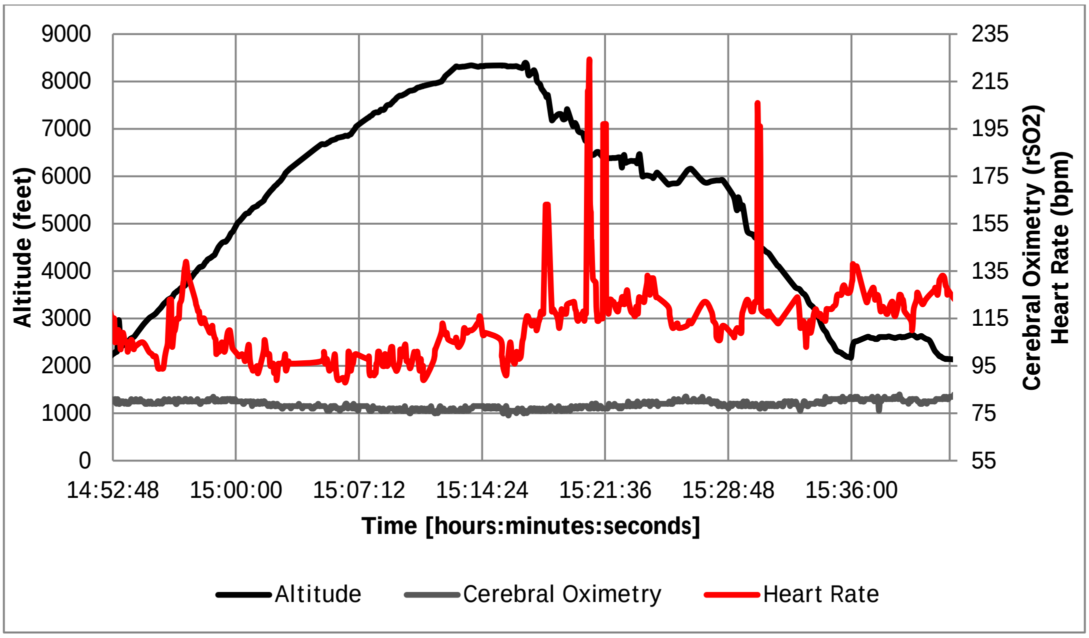
Graphic 8: Altitude, rSO2 and HR variation during the real flight, test 2.

In Graphic 9 may be seen that the third test (3) had a maximum altitude of 6,433 ft above sea level and had duration of, approximately, two hours and fifty six minutes. At the beginning of the test the rSO2 mean value was 62%, by the moment before the first descent (15:52:25), at 6,264 ft, the rSO2 reached the minimum value of 56%, and then starts to increase, while at a 6,258 ft altitude, until the end of the first descent (16:36:21), at 693 ft. Then, the oscillation of the rSO2 values become higher and by the start of the second descent (17:21:29), at 6,270 ft, it starts increasing, until the end of the flight. The rSO2 mean value, during the flight, was 61.8%, with a standard deviation of 2.7%. It may also be seen that there were three expressive peaks in the HR, the first at the beginning of the flight (15:02:07), the second by the end of the first descent (16:33:19) and the third slightly before the last descent (17:48:17), where it reached the 93 bpm, 89 bpm and 88 bpm, respectively. Also, was possible to observe that the HR starts decreasing a few moments after the aircraft reached the maximum altitude (15:32:59), at 6,433 ft, and then increases again when he is about to start the first descent. The mean value, during the flight, was 76 bpm with a standard deviation of 5.2 bpm.



Graphic 9: Altitude, rSO2 and HR variation during the real flight, test 3.

In Graphic 10 may be seen that the fourth test (4) had a maximum altitude of 8,394 ft above sea level and had duration of, approximately, fifty two minutes. At the beginning of the test the regional oxygen saturation (rSO2) mean value was 81%, which corresponded to the maximum absolute value recorded during the entire test. The minimum rSO2 absolute value, 74%, was recorded when the maximum altitude was reached (15:15:57). Besides those moments, the rSO2 value was practically the same during the entire test, with a mean value of 78.8% and a standard deviation of 1.76%. It may also be seen that there was a negative followed by a positive peak in the HR value by the moment the aircraft starts to climb to the maximum altitude, and then, until the end of the ascent, the HR stands, approximately, constant, with a mean value of 105 bpm. During the descent manoeuvres, the HR reached several peaks, where the most expressive was 223 bpm (15:20:41). Then, closer to the ground the HR stabilizes again. During the entire flight, the HR had a mean value of 115 bpm with a standard deviation of 18.3 bpm.



Graphic 10: Altitude, rSO2 and HR variation during the real flight, test 4.

3.4 Conclusion

The analysed survey examined a heterogeneous sample of pilots whose field experiences and perceptions were different, whereby the generalizability of these results should be considered. Once the studied individuals are a small segment and an unbalanced mixture of the entire pilots' population, these findings may not generalize to pilots overall. The factors mentioned above could have affected the observations found in the current analysis. Besides its limitations, this inquest provided interesting and useful information that can positively contribute to flight safety. This survey was available online for all pilot's community, but due to the lack of adherence and disclosure to this initiative, until the closure of this dissertation, a more precise and wider range of results wasn't possible to obtain.

The experimental work consisted in the combination of different equipment in order to obtain synchronization between the physiological parameters, as cerebral oximetry and HR, and the flight data, as altitude, temperature and humidity. The main purpose of this combination was to be able to study the physiological differences, when the pilot is at rest and when he is performing tasks, and how relevant these differences are in flight safety, taking in consideration various environmental scenarios. Although, besides the lack of tests and tested individuals, important data and observations were obtained.

4. Discussion

4.1 Introduction

In this chapter, the obtained results in both the survey and the experimental work, mentioned in the previous chapter, will be discussed.

Following the same organizational structure, the current chapter was divided into two parts. The first part concerning the analysis and discussion regarding the survey results and the second referring to the hypobaric chamber and real flight tests.

4.2 Survey

Hypoxia is a concerning situation not only for those who fly in pressurized aircraft cabins but also for those who fly below 10,000 ft in unpressurized aircraft cabins. The studied sample population was constituted by a very heterogeneous pool of pilots, where most of it reported that the majority of the performed flights, in the six months preceding the survey, took place in unpressurized aircraft cabins at a maximum ceiling altitude of 10,000 ft. From this restrict range of pilots was possible to observe that half of them had felt, at least, one of the addressed hypoxia symptoms, but only 44% had received hypoxia training.

Despite the fact, that the pilots who usually fly above 10,000 ft were significantly less than those who usually fly below, the results demonstrated that hypoxia is also a very concerning subject at high altitudes performed flights.

Providing education about hypoxia symptoms and how to react before them within a supervised ground location was considered crucial for most of the respondents, with only a few exceptions. In the original U.S survey [39], about 92% of the individuals agreed with a basic introductory hypoxia course (not including ACT), 84% with a recurrent ACT and 85% with an initial ACT. In the current inquest, also most of the pilots agreed with the basic introductory hypoxia course (not including ACT) (79%) and with the initial ACT (57%), but less than half believed in a recurrent ACT (22%).

When questioned if the current aeromedical regulations (i.e., not requiring ACT) are sufficient, about 39% of the respondents disagreed or strongly disagreed.

Regarding the statement that the need for training in hypobaric chamber should be established according to the maximum altitude of the operated aircraft, the majority the pilots agreed with it. Also, over than half of the current inquest individuals (56%) believed that the type of pilot license should directly contribute to the determination of who needs ACT.

The obtained answers regarding the education and training on hypoxia fundamentals revealed that there is a concern in this matter, but there's also a significant dissatisfaction as to how the current legislation stares.

When specific hypoxia training needs were assessed for fourteen types of pilot certification, most of the pilots perceived the need for an introductory hypoxia course (without ACT) as necessary, especially for ultralight pilots. The respondents also believed that the type of certification was relevant for initial ACT, particularly for commercial and those who commonly fly in pressurized aircraft cabins, than for recreational pilots. Although, as stated earlier, the majority of the pilots who reported to have experienced some of the hypoxia symptoms were those who usually fly in unpressurized cabins, at a maximum ceiling of 10,000 ft.

From those who have light aviation license and normally fly below 10,000 ft, 42% believed in an initial ACT for recreational flight certification types.

The statistical analysis regarding the unpressurized aircraft pilots showed that this particular population is the one that both survey's respondents considered less significant, regarding hypoxia education and training. Although, the lack of education in the hypoxia subject, demanded for light aviation license, combined with each individual integrity and responsibility, shouldn't be neglected, especially in this type of aviation where the legislation is less restrictive and where the accidents/incidents are many.

Two of the key questions of the survey aimed to evaluate how relevant a physiological monitoring system would be considered important for pilot's flight safety. The results analysis proved that, besides the fact that most of the sample population reported that had never felt any hypoxia symptom, almost all pilots found this system useful and affirmed to be willing to use it.

4.3 Experimental Work

In the hypobaric chamber tests, was possible to observe that despite of the difference of age between both individuals, the eldest individual showed inferior levels of HR and a minor variation of the rSO2, when compared with a much younger individual. However, the eldest individual, individual 2, was a flight instructor with many hours of experience and many hypoxia trainings in hypobaric chamber. For the individual 1, the experimental test was his first time in the hypobaric chamber. These differences, in levels of experience and life habits, may be the main cause for the disparity of values between the subjects.

Upon comparison of cerebral oximetry and HR with the altitude variation in both tests, was observed that, in the hypobaric chamber test, where the maximum reached altitude was 9,577.9 ft, the rSO2 and HR variation, between the minimum and maximum altitude, was 3% and 4%, and 14 bpm and 5 bpm, for individual 1 and individual 2, respectively. In the real flight tests, for the test 1, the rSO2 and HR variation, between the minimum and maximum altitude, was 2% and 3 bpm, for the test 2, was 2% and 2 bpm, for the test 3, was 1% and 5 bpm, and for the test 4, was 3% and 7 bpm, respectively. However, was also found that the minimum value of rSO2 and the maximum HR did not occur when the maximum altitude was reached, as expected. Such inconsistency does not have an apparent justification due to the scarce information available for this type of study, so, and only as a superfluous suggestion, these may be due to psychophysiological characteristics, such as concentration, attention, adrenaline, emotional condition or even the reaction time that the human body takes to respond to the external environment.

For individual 1, was possible to observe that the variation of the rSO2, between the maximum and the minimum altitude, was smaller during the real flight test (real flight test 4) than during the hypobaric chamber test. Although, besides the fact that the real flight was performed at a lower altitude, and so this smaller variation may be justified, according to what is generally known, the pilot wasn't at rest and his initial rSO2 mean value was, approximately, 3.5% higher when compared with the obtained values from the hypobaric chamber test. However, the HR variation was significantly higher for the real flight test.

For individual 2, it was possible to observe that the variation of the rSO2 and the HR values was smaller when he was at rest (hypobaric chamber) and at a higher altitude, than when he was performing tasks (real flight tests) but flying at a lower altitude. Although, in the real flight test 2, where the atmospheric conditions weren't the best, with strong wind, the pilot rSO2 and HR values oscillated expressively, not in the higher altitude moments, but when the aircraft wasn't stabilized due to the wind. In the real flight test 3, was found that in comparison with the hypobaric chamber test, where the simulated altitude was, approximately, 3,000 ft higher, the rSO2 and HR variation was more pronounced.

Also, from the cerebral oximetry analysis for both individuals, regarding both tests, can be seen that they had different basis values of rSO2, which may happen due to the disparity of quotidian habits and physical characteristics; and that sporadic peak values occur, because, in both cases, the studied pilots weren't completely immobile and therefore, there was the susceptibility of poor contact with the cerebral oximetry sensors. Although, still, and in the near future, these data have to be carefully analysed by clinical experts in the determination of the existence or not of significant changes, that may constrain the psychophysiological capacity and, consequently, compromise the flight safety.

In conclusion, the discussed results may show that the human body can be trained to adapt to different situations and that when under an unknown environment, the stress, arousal and adrenaline levels may compromise the initial rSO2 and HR values and the normal response to an external stimulus, increasing, psychologically, its intensity.

4.4 Conclusion

Generally, most of the respondent pilots considered that hypoxia education and training for unpressurized aircraft pilots isn't significant. Although, almost all the respondents affirmed to be willing to use a flight physiology monitoring system, in order to improve flight safety.

Could be found that factors as arousal, stress, fear and adrenaline, processed by our brain due to an uncontrolled and unpredictable environment, may be even more dangerous than a physical and logical factor like altitude, especially if the individual isn't aware of his physiological limits.

In short, it is general belief that this is an interesting and justified research that deserves the best attention, as also as an exhaustive research in the psychophysiological field, in order to understand the human behaviour when an unpredictable and stressing situation is combined with oxygen deprivation.

5. Conclusion

5.1 Dissertation Synthesis

The practice of gliding and ultralight aviation in Portugal has been growing in the past few years and with it the responsibility to make this an activity even safer for those who fly and those who are in the ground. Simultaneously, it has been found that accidents and incidents, with no apparent mechanical causes, have also suffered an increment, and that some pilots after returning from their flights, reported having noticed in themselves, while performing the flights, euphoria, decreased reaction time, and inability to perform simple tasks. Therefore, these symptoms report a variation in the psychophysiological response compatible with the phenomenon of hypoxia that, in terms of flight safety, may represent a worrying situation.

For this study contextualization some parameters regarding the flight physiology were analysed. The notion of the hypoxia phenomenon and its associated symptoms and concepts, as partial pressure of oxygen and time of useful consciousness (TUC) were presented. As well as other parameters as heart rate (HR), respiratory rate (RR) and cerebral load activities. Complementarily, a scan to the World, North American, European and Portuguese aeronautical legislation, regarding the limitations for unpressurized aircraft cabins aviation, was also made. Particularly, was noted that the general legislative framework merely makes altitude and time restrictions, with or without supplemental oxygen support, not taking into consideration that the psychophysiological response to an external stimulus depends on many factors and is different for each individual.

In the case study two researches were made in parallel: the first was the statistical analysis of an online survey about the flight physiology, emphasizing the phenomenon of hypoxia (symptoms, impacts on the pilots performance, and possible preventive solutions), developed by Rocha [1], specifically directed to general aviation in Portugal; the second consisted in the collection of physiological data, cerebral oximetry and HR, synchronized with the flight parameters as altitude, temperature and humidity, in a simulated environment, hypobaric chamber, and in real flight scenarios.

In the end, the obtained results from the survey's statistical analysis were discussed, as well as both cerebral oximetry and HR results, obtained from the experimental tests. On one hand, was possible to conclude that, in Portugal, pilots are aware and conscious about the phenomenon of hypoxia, but they wish to have more training in this area – including specific training in hypobaric chamber. Part of them are also not fully satisfied with the current legislation, regarding the flight physiology, and consider useful the development of monitoring systems in order to quantify objectively, in flight and in real time, the pilot's performance and responsiveness, aware that this could positively contribute to flight safety.

On the other hand, was also possible to conclude that hypoxia isn't the only phenomenon that can compromise the pilot's performance. Physiological reactions to the psychological factors combined with the environmental conditions, as arousal, stress, adrenaline, fear and fatigue, can highly influence the human body physiological response. Such parameters, analysed separately, can even surpass the physical and logical reaction caused by the decrement of the partial pressure of oxygen. However, the combination of both may cause an even bigger and potentially dangerous reaction that will surely depend on a long time scale factors, as everyday habits, physiological characteristics and experience level, and a diary time scale factors, as emotional and physical condition.

5.2 Final Considerations

The Flight Physiology concept is taken into high consideration in the commercial and military aviation, but the competent authorities, in general aviation, have neglected it's applicability to pilots who fly in unpressurized and unacclimatized aircraft cabins, namely, the glider, ultralight and light aircraft pilots. This is an even more serious problem once, today, the general sport aviation is a booming business throughout the world, and the regulatory frameworks of the different countries aren't following this growth and are currently outdated of reality and its needs.

The Flight Physiology concept can embrace many different parameters and scenarios and be influenced by several factors that can manifest themselves in various ways, once each human being is unique, whether a physiological or psychological level. To be able to calmly and timely react to those manifestations the pilot need to be aware of his own symptoms and limits. However, a sporadic training in flight physiology fundamentals, with ACT, wouldn't be enough, once the human body is highly susceptible to the diary habits and psychological conditions. There is much literature regarding different parameters embraced by the flight physiology concept, although there aren't many empirical studies that corroborate them in real scenarios.

The work of Rocha in 2011 [1] served as motivation for the current one, as though the phenomenon of hypoxia, in sport aviation, has been identified, but the lack of experimental tests and analysed parameters didn't allow a strong support for a legislation change in this type of aviation. In this sense, more physiological parameters were analysed and studied in different flight scenarios, as well as a more ergonomic, compact and user-friendly monitoring system was built.

During this study there were various experimental flights, where only in those analysed in the current dissertation was possible to extract the full data. Due to the uniqueness and innovation of this project part of the hardware and software used were developed in partnership with other colleagues from the Department of Informatics of University of Beira Interior, so that the field work became quite time consuming. During the hardware and software construction some difficulties appeared, mainly related to the cost and availability of the equipment and its internal system decoding. Due to these obstacles it wasn't possible to integrate the EEG and the EP system, by the disclosure of this work. Also, some difficulties, mainly related to the availability of pilots and/or aircrafts for the tests, were faced.

The factors mentioned above are the main reason for the lack of experimental tests and variety regarding the physiological parameters analysis; however, besides its limitations this study provides unique and useful information that can positively contribute to flight safety.

Based on the current work, a presentation in the 52nd European Regional Science Association (ERSA), in Bratislava, was also accomplished.

Flight physiology is a vast field of research, where are many unexplored situations, particularly related to the light aviation, that deserves our best concern; so in order to improve safety for everyone was also this research intention to answer to some of the national legislation flaws. However, due to the above mentioned motives, the study isn't solid enough to successfully support the changes in the national legislation.

5.3 Prospects for Future Work

Due to the current work and acquired knowledge and experience it's believed that the next steps in this work should cross the following investigation lines:

- Validate the implementation, in the current system, of the EEG and EP;
- Extend the field tests to the flight simulator, which purpose is also studying the pilot psychophysiological behaviour during situations of attention and concentration, while he is in a fictional environment;
- Combine the used monitoring systems with a live alert software, in order to warn the pilot when his limits are crossed, and so he can recall the safety procedures;
- Create an internal network system, where the collected data can be transmitted, live, to a ground equipment;
- Apply for a potential restriction to pilots licensing legislation of light aviation, within definitions of physiological limits.

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Annex 1

Portuguese Survey [1]

Hipóxia em Aviação Geral

Mestrado em Engenharia Aeronáutica - Leandro Rocha | Doutoramento em Medicina - Luís Patrão
Universidade da Beira Interior - Covilhã

Este inquérito é de preenchimento voluntário e destina-se a pilotos de aviação com licença válida, independentemente da classe ou tipo da mesma. Insere-se no âmbito do Mestrado em Engenharia Aeronáutica de Leandro Rocha e do Doutoramento em Medicina de Luís Patrão, ambos pela Universidade da Beira Interior, estando a orientação científica a cabo dos Professores Doutores Jorge Miguel Reis Silva e Miguel Castelo Branco, respectivamente. Este inquérito conta com o apoio da Direcção de Certificação Médica do Instituto Nacional de Aviação Civil, I.P.

Este inquérito foi adaptado de um outro, em língua inglesa, que serviu de base ao artigo *Hackworth C, Peterson L, Jack D, Williams C. Altitude training experiences and perspectives: survey of 67 professional pilots. Aviation, Space and Environmental Medicine 2005 Apr;76(4):392-4*. A primeira autora foi contactada e deu autorização para o uso, sem reservas, do inquérito original.

O objectivo deste inquérito é a recolha de informação sobre situações de hipóxia ou descompressão, distinguindo-se do original em inglês pela adaptação à aviação geral. Os resultados serão um ponto de partida para trabalhos futuros podendo ser úteis na definição de novos protocolos de formação e treino de situações de hipóxia.

Caso surja alguma dúvida durante o preenchimento do inquérito, por favor não hesite em enviar um email para luispatrao (at) fcsaude (ponto) ubi (ponto) pt

Os autores desde já agradecem a sua colaboração.

Existem 41 perguntas neste inquérito

Uma nota sobre privacidade

Este inquérito é anónimo.
O registo guardado das suas respostas ao inquérito não contém nenhuma informação identificativa a seu respeito, salvo se alguma pergunta do inquérito o pediu expressamente. Se respondeu a um inquérito que utilizasse um código identificativo para lhe permitir o acesso, pode ter a certeza de que o código identificativo não foi guardado com as respostas. É gerido numa base de dados separada e será actualizado apenas para indicar se completou ou não este inquérito. Não é possível relacionar os códigos de identificação com as respostas a este inquérito.

Inquérito

***Qual a sua idade?**

[ ] anos.

***Qual o seu género?**

○ Feminino ○ Masculino

***É ou já foi fumador?**

○ Sim, sou fumador ○ Não sou actualmente mas já fui fumador ○ Não sou nem nunca fui fumador

***Pratica exercício físico com regularidade?**

○ Sim ○ Não

***Pratica mergulho com regularidade?**

○ Sim ○ Não

***A actividade que desempenha ou já desempenhou em toda a sua vida como piloto insere-se em qual ou quais destas categorias?**
Seleccione todas as que se apliquem

☐ Aviação Geral
☐ Aviação Militar
☐ Transporte aéreo internacional
☐ Transporte aéreo regional
☐ Taxi-aéreo
☐ Corporate

***Possui qual ou quais das seguintes licenças de voo?**
Seleccione todas as que se apliquem

☐ Piloto de ultraleve
☐ Piloto de planador
☐ Piloto particular de avião
☐ Piloto particular de helicóptero
☐ Piloto particular de motoplanador
☐ Piloto particular de balão
☐ Piloto comercial de avião
☐ Piloto comercial de helicóptero
☐ Piloto comercial de balão
☐ Piloto de linha aérea de avião
☐ Piloto de linha aérea de helicóptero
☐ Instrutor do voo de ultraleves
☐ Instrutor de voo de ligeiros
☐ Instrutor de voo de linha aérea
☐ Instrutor de voo com instrumentos

***A sua principal actividade profissional é piloto ou instrutor de voo?**

○ Sim ○ Não

***Qual é a licença médica que possui actualmente?**

○ Classe 1
○ Classe 2
○ Classe 3

***Indique a marca e modelo da aeronave que pilota com mais frequência.**

[ ]

***A maioria dos voos que efectuou nos últimos 6 meses foi em aeronaves pressurizadas?**

○ Sim ○ Não

***Qual o total de horas que voou como piloto e/ou instrutor?**

[ ] horas de voo

Neste campo só se aceitam números

***Quantas horas voou como piloto e/ou instrutor nos últimos 6 meses?**

[ ] horas de voo

horas de voo

Neste campo só se aceitam números

***Qual a percentagem de tempo de voo como piloto e/ou instrutor que, nos últimos 6 meses, foi durante o dia vs. durante a noite?**

Por favor, seleccione...

O primeiro valor refere-se ao período diurno e o segundo ao período nocturno.

***Qual a percentagem de tempo de voo como piloto e/ou instrutor que, nos últimos 6 meses, foi por lazer/desporto vs. obrigações profissionais?**

Por favor, seleccione...

O primeiro valor refere-se a lazer/desporto e o segundo a obrigações profissionais.

***Qual a percentagem de tempo de voo que, nos últimos 6 meses, voou como piloto vs. instrutor?**

Por favor, seleccione...

O primeiro valor refere-se a tempo de voo exclusivamente como piloto e o segundo a tempo de voo como instrutor de voo.

***Qual a altitude, em pés, a que voa habitualmente?**

pés

Neste campo só se aceitam números

Considere que, por exemplo, 30000 pés correspondem ao FL300.

***Qual a percentagem de tempo de voo que, nos últimos 6 meses, voou em aeronaves com motor alternativo vs. turbina?**

Por favor, seleccione...

O primeiro valor refere-se a tempo de voo em aeronaves com motor alternativo o segundo a aeronaves com turbina.

***Em média, qual a percentagem do seu tempo de voo realizado nas seguintes altitudes (QNH)?**
A soma deve totalizar 100

Nestes campos só podem sem inseridos números

até aos 5000 pés
entre os 5001 e os 10000 pés
entre os 10001 e os 13000 pés
entre os 13001 e os 15000 pés
entre os 15001 e os 25000 pés
entre os 25001 e os 30000 pés
entre os 30001 e os 35000 pés
entre os 35001 e os 40000 pés
entre os 40001 e os 43000 pés

acima dos 43000 pés	
Restantes:	*100*
Total:	***0***

Considere que, por exemplo, 30000 pés correspondem ao FL300.

***Concorda com a afirmação de que, nas altitudes e condições em que voa normalmente, não há qualquer perigo de estar sujeito a situações de hipóxia?**

○ Sim ○ Não

***Já realizou formação ou treino sobre hipóxia em aviação?**

○ Sim ○ Não

***Indique o seu nível de concordância com as seguintes afirmações:**

	1	2	3	4	5
Todos os pilotos deveriam fazer um treino básico de introdução à hipóxia (sem treino em câmara hipobárica)	○	○	○	○	○
Todos os pilotos deveriam fazer um treino periódico sobre hipóxia (sem treino em câmara hipobárica)	○	○	○	○	○
Todos os pilotos deveriam fazer um treino básico em câmara hipobárica	○	○	○	○	○
Todos os pilotos deveriam fazer um treino periódico em câmara hipobárica	○	○	○	○	○
As regulamentações aeromédicas actuais, no que toca à formação e treino de situações de hipóxia, são suficientes	○	○	○	○	○
A necessidade de treino em câmara hipobárica deveria ser estabelecida em função da altitude máxima das aeronaves pilotadas pelo piloto em causa	○	○	○	○	○
A necessidade de treino em câmara hipobárica deveria ser estabelecida em função do tipo de licença de voo do piloto	○	○	○	○	○

1 - Discordo totalmente | 2 - Discordo | 3 - Nem concordo nem discordo | 4 - Concordo | 5 - Concordo plenamente

***Que tipo de formação em hipóxia considera que os pilotos a seguir descritos deveriam possuir?**

	Não precisa de formação em hipóxia	Curso básico de introdução à hipóxia (sem treino em câmara hipobárica)	Curso periódico sobre hipóxia (sem treino em câmara hipobárica)	Curso que incluiu treino em câmara hipobárica	Curso periódico em câmara hipobárica

Piloto de ultraleve	○	○	○	○	○
Piloto de planador	○	○	○	○	○
Piloto particular de avião	○	○	○	○	○
Piloto particular de helicóptero	○	○	○	○	○
Piloto particular de motoplanador	○	○	○	○	○
Piloto particular de balão	○	○	○	○	○
Piloto comercial de avião	○	○	○	○	○
Piloto comercial de helicóptero	○	○	○	○	○
Piloto comercial de balão	○	○	○	○	○
Piloto de linha aérea de avião	○	○	○	○	○
Piloto de linha aérea de helicóptero	○	○	○	○	○
Instrutor de voo	○	○	○	○	○
Pilotos de aviação geral que voem aeronaves não pressurizadas	○	○	○	○	○
Pilotos que voem aeronaves pressurizadas	○	○	○	○	○

***Alguma vez se encontrou perante uma situação de hipóxia em voo?**

	Sim	Não
Como aluno-piloto	○	○
Como piloto	○	○
Como co-piloto	○	○
Como instrutor	○	○
Como membro de uma tripulação	○	○

Como membro de uma tripulação

Como passageiro

***Qual ou quais dos sintomas seguintes já sentiu ou observou em si enquanto voava e que funções desempenhava nesse momento?**

	Aluno-piloto	Piloto	Co-piloto	Membro da tripulação	Instrutor	Passageiro	Nunca senti
Sensação de falta de ar							
Alterações visuais							
Falta de coordenação dos movimentos							
Sensação súbita de calor ou de frio							
Aumento da profundidade da respiração ou da frequência respiratória							
Euforia							
Dor de cabeça							
Aumento do tempo de reacção							
Dificuldade em tomar decisões							
Tonturas							
Náuseas							
Formigueiros nos dedos das mãos e/ou dos pés							
Fadiga, cansaço ou sonolência							
Sensação de falta de ar							
Cianose (as extermidades e/ou os lábios ficarem azuis/arroxeados)							
Alterações do discurso							
Dificuldade em decorar informações e/ou instruções							

Quando se encontrou perante situações de hipóxia ou quando sentiu os sintomas referidos na pergunta anterior, que medidas tomou para resolver

essa situação?

***Em voo, já esteve perante uma situação de descompressão?**

	Sim	Não
Como aluno-piloto	○	○
Como piloto	○	○
Como co-piloto	○	○
Como instrutor	○	○
Como membro de uma tripulação	○	○
Como passageiro	○	○

Explicite quaisquer outras informações sobre hipóxia e descompressão que considere úteis e que sejam fruto da sua experiência enquanto piloto.

***Considera que seria útil o desenvolvimento de sistemas de monitorização e quantificação objectiva, em voo e em tempo real, da capacidade de resposta do piloto?**

○ Sim ○ Não

***Utilizaria um sistema como o descrito na questão anterior se tal contribuísse para a segurança de voo?**

○ Sim ○ Não

Carregar inquérito incompleto

Continuar mais tarde

Submeter

Sair e limpar inquérito