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# Physiological Effects on Scientist Astronaut Candidates: Hypobaric Training Assessment

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# Physiological Effects on Scientist Astronaut Candidates: Hypobaric Training Assessment

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***Abstract*—**This paper is addressed to expanding our understanding of the effects of hypoxia training on our bodies to better model its dynamics and leverage some of its implications and effects on human health. Hypoxia training is a recommended practice for military and civilian pilots that allow them to recognize their early hypoxia signs and symptoms, and Scientist Astronaut Candidates (SACs) who underwent hypobaric hypoxia (HH) exposure as part of a training activity for prospective suborbital flight applications. This observational-analytical study describes physiologic responses and symptoms experienced by a SAC group before, during and after HH exposure and proposes a model for assessing predicted versus observed physiological responses. A group of individuals with diverse Science Technology Engineering Mathematics (STEM) backgrounds conducted a hypobaric training session to an altitude up to 22,000 ft (FL220) or 6,705 meters, where heart rate (HR), breathing rate (BR) and core temperature (Tc) were monitored with the use of a chest strap sensor pre and post HH exposure. A pulse oximeter registered levels of saturation of oxygen ($SpO_2$), number and duration of desaturations during the HH chamber flight. Hypoxia symptoms as described by the SACs during the HH training session were also registered. This data allowed to generate a preliminary predictive model of the oxygen desaturation and $O_2$ pressure curve for each subject, which consists of a sixth-order polynomial fit during exposure, and a fifth or fourth-order polynomial fit during recovery. Data analysis showed that HR and BR showed no significant differences between pre and post HH exposure in most of the SACs, while Tc measures showed slight but consistent decrement changes. All subjects registered $SpO_2$ greater than 94% for the majority of their individual HH exposures, but all of them presented at least one clinically significant desaturation ($SpO_2$ < 85% for more than 5 seconds) and half of the individuals showed $SpO_2$ below 87% for at least 30% of their HH exposure time. Finally, real time collection of HH symptoms presented temperature somatosensory perceptions (SP) for 65% of individuals, and task-focus issues for 52.5% of individuals as the most common HH indications. 95% of the subjects experienced HH onset symptoms below FL180; all participants achieved full recovery of HH symptoms within 1 minute of donning their $O_2$ mask. The current HH study performed on this group of individuals suggests a rapid and fully reversible physiologic response after HH exposure as expected and obtained in previous studies. Our data showed consistent results between predicted versus observed $SpO_2$ curves during HH suggesting a mathematical function that may be used to model HH performance deficiencies. During the HH study, real-time HH symptoms were registered providing evidenced SP and task focusing as the earliest and most common indicators. Finally, an assessment of HH signs of symptoms in a group of heterogeneous, non-pilot individuals showed similar results to previous studies in homogeneous populations of pilots.

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## I. Introduction

Atmospheric flight poses various stresses to human physiology; modern aerospace operations counteract human limitations with leading-edge technology in order to mitigate safety risks. One of these safety risks is physical and/ or cognitive impairment preventing flight crews to perform flight duties in a safe manner, and HH is one of the main hazards that might lead to impaired performance. Hypoxia can be defined as the incapacity for cells, tissues, and organs to utilize oxygen, interfering with normal cellular respiration processes [2], [5]. These oxygen utilization abnormalities can occur during the uptake, pulmonary ventilation, bloodstream transport or oxygen usage by the cells and tissues, which results in deteriorated performance in terms of sensory perception, psychomotor abilities, cognitive resources, and complex decision-making [26]. Examples of hypoxia signs are rapid breathing, poor coordination, lethargy, executive impairment, and poor judgment, cyanosis (bluish tone of the skin), diaphoresis (sweating), trembling, and myoclonic (muscle) spasms. Along with hypoxia signs, subjects can develop hypoxia symptoms, such as air hunger, fatigue, nausea, headache, dizziness, hot-cold flashes, tingling, visual impairment, euphoria, and tachycardia [8]-[10], [23]. Various studies have reported hypoxia symptoms at various altitudes depending on the individual level of susceptibility. For example, hypoxia symptoms are visible in most healthy individuals after reaching 10,000 ft., but it may be present at lower altitudes for some individuals and be absent at higher altitudes for some other participants [12]. Other studies state that hypoxia symptoms may occur in healthy personnel at altitudes higher than 11,811 ft. (3,600 m) and most incidents related to hypoxic states have occurred at altitudes below 19,000 ft. (5,791 m) [23].

Because of the hazard of flawed human performance, HH has been a long-lasting concern for aerospace safety [11]. Even though real-time data related to human performance in real-world operations is hard to retrieve and analyze, numerous simulation scenarios and performance models have been developed in order to study signs, symptoms, and precursors to human impairment and incapacitation due to hypoxic states. HH has been linked with impairment in various aspects of human performance [31]. It is well established that its effects on the central nervous system (CNS) are not only the most relevant in terms of human performance but also, the first ones to be evident, especially in oxygen-avid tissues such as the retina [27]. Relevant results in hypoxia research indicate that exposed individuals may experience mild decrements in reaction time as low as 10,000 ft., but overall, HH produced consistent detrimental effects on short-term memory, pattern recognition, and psychomotor skills in altitude settings above 10,000 ft. Moreover, it is understood that some cognitive functions remain slightly impaired during a brief post-exposure window [1], [3], [7], [26]. In addition, hypoxia effects [25] on cognitive abilities are strongly related to the complexity of the tasks and the vulnerability of the different cognitive functions to be affected, showing that mathematical and auditory processing are especially prone to hypoxic conditions [7]. It is also widely accepted that HH effects, especially those on the CNS, rely not only on the exposure altitude (which dictates the relative partial oxygen pressure ($PO_2$) of the environment), but also the onset and the duration of the exposure to that reduced $PO_2$.

It is accepted that the onset, intensity, and development of subjective sensations derived from HH exposure are widely variable. That erraticism has been evident in most of the research protocols related to HH and is linked mainly to epigenetic influences and exposure variability, but also due to the transposition of hypocarbia symptoms, usually associated with early hypoxia exposure [26], [29], [33]. Various HH training and research protocols include validated acute mountain sickness (AMS) scales for reporting HH symptoms, but most of these inventories include a closed list that not always reflect all HH possible symptoms [27]. It is also known about HH symptoms assessment that the extent to which memory impairment can affect the recalling of perceptions and sensations of the participants during HH exposure might be an issue. Knowing that memory is one of the most fragile human cognitive resources and retention and encoding are certainly impaired by HH, it is expected that symptoms recalling, and recognition would also be affected during and after HH exposure [35]. Nevertheless, understanding and recalling hypoxia symptoms is critical for aircrews so they can make critical safety decision [13], [17], [34] such as donning emergency oxygen systems, performing an emergency descent, looking after smoke or toxic fumes or even evacuating the aircraft; all of this while ideally maintaining constant communications with ground stations [15]. To that end, hypobaric training for crews is an essential tool that allows crewmembers to experience and assess their own hypoxia signs and symptoms, so they can recognize HH states and trigger remedial actions. The goal of HH training is to expose participants to a hypobaric environment (altitude chamber), inducing signs and symptoms associated with hypoxia that the participants can recognize on their own bodies, and to demonstrate cognitive deterioration during the exposure [32]. Hypoxia physiology training has been recommended by international safety regulators for a long time. Furthermore, the International Association for the Advancement of Space Safety (IAASS) recommends HH training for spaceflight operations, including the suborbital domain.

The Polar Suborbital Science in the Upper Mesosphere (PoSSUM) is a non-profit organization with a goal to study the noctilucent clouds in the mesosphere to enhance our understanding of the aeronomy and climate change science. PoSSUM program has been training over 100 subjects with diverse backgrounds, ethnicity, gender and age since 2015. As part of their training, subjects from across the globe meet to conduct different scientific activities related to human air and space exploration. The HH training takes place at the Southern Aeromedical Institute (SAMI) in Melbourne, Florida.

In this study, we assessed the effects of exposure to HH on various subjects during their training in a hypobaric environment. Thus, this observational-analytical study describes physiological responses experienced by PoSSUM participants and proposes a mathematical model which could be used to predict levels of oxygen desaturation as a function of pressure, during exposure to HH and during recovery after donning the oxygen mask to facilitate oxygen delivery.

## II. Procedure and Methods

### A. Subjects

This study was based on a research protocol reviewed and approved by the Institutional Review Board (IRB) at Embry-Riddle Aeronautical University, Daytona Beach campus. Each participant or subject, referred to as SAC [19], provided written informed consent before taking part in the hypobaric runs. These SACs had previously obtained a valid FAA Class III medical certificate and were asked to fill a pre-exposure health assessment questionnaire (template is attached as supplemental information) used for screening common health condition.

Initially, 40 subjects participated in the hypobaric training. Out of these, 18 subjects wore real-time registering wearables before and after the chamber flight, and the data from these subjects will be analyzed.

All subjects were active individuals who exercised less than 5 days a week and were not considered part of an elite population of athletes (exercise more than 5 days a week).

### B. Materials

Each subject wore a Zephyr® Bioharness (ZB) [36] to collect physiological data before and after the hypobaric flight: ZBs recorded HR, BR, core [22] and device temperatures (T), and posture. In addition, other hemodynamic values, such as systolic pressure (SP), diastolic pressure (DP) and mean arterial blood pressure (MAP) were also collected before and after each hypobaric flight in the chamber using a wgnbpa-945 sphygmomanometer [20]. During the exposure, individuals always wore a SPO medical pulse oximeter sensor, which provided continuous readings of blood oxygen levels (Blood $O_2$ saturation ($SpO_2$)) and HR. This device was placed at the index fingertip and had USB capability to be connected to a computer where channels $SpO_2$ and pulse rate was recorder. The SAMI provided hypoxia training to the subjects. The hypobaric chamber, founded in 1999, has trained over 3,000 pilots to help pilots better understand the dangers of "slow onset hypoxia" or altitude sickness. The SAMI personnel as observers from outside the hypobaric chamber detected these symptoms or sensations. Expert SAMI personnel observed on screens outside the chamber, looking for HH signs and symptoms in the subjects during the hypobaric flight. Quantitative and qualitative data were collected by SAMI observers: They registered vital signs, HH signs and symptoms and the overall performance of the participants during the exposure. SAMI was equipped with Zodiac Aerospace EROS MC 10 MXP6 oxygen mask that was worn by SACs when they reached a hypoxic state which was articulated by the SAMI personnel.

All data were collected, analyzed and processed in Microsoft Excel software. Data are presented as mean ± standard deviation (SD) for each subject.

### C. Hypobaric Chamber Environment

For each hypobaric run, two SACs entered the hypobaric chamber at a time, and an additional third subject from SAMI joined them inside the chamber as a support technician. Each SAC took a different station where a TBM 850 flight training simulator was set. Each subject wore a communication headset to communicate with the support staff inside the chamber and with SAMI support personnel outside the chamber. Subjects were asked to report HH symptoms using this communication device in order to be registered by the observing personnel in real-time. An oxygen mask was placed next to each station and a pulse oximeter sensor was set on each candidate's index registering the saturations of oxygen ($SatO_2$) continuously.

### D. Hypobaric Exposure

Participants were instructed for 30 minutes about "slow onset hypoxia" including a basic introduction to aviation physiology, and a review of accidents due to slow-onset hypoxia. After this short lecture, participants were given a 30-minutes pre-flight orientation about the flight simulators and oxygen mask utilization (emergency mask donning), then, participants entered the hypobaric chamber for approximately 30 minutes. The high-altitude chamber training flight started at 5,000 ft. with an ascent rate of about 2,000 ft. per minute, the SACs were then asked to perform a flight-training task (FTT), with the objective of following certain flight vectoring directions as instructed by SAMI personnel. During the FTT, the participants were also asked to be alert of arising HH symptoms derived from this slow-onset hypoxia exposure. First, the SAMI personnel began to decrease the cabin pressure up to 5,000 ft to slowly adapt the subjects to pressure shifts, and then the cabin pressure was brought back to ground altitude. Following, the cabin pressure was decreased until approximately 20,000-22,000 ft. high equivalent. SAMI personnel closely monitored the participants while maintaining constant communication with them ascertaining their individual hypoxia sensations. Every 2,000 ft (or 1 minute given the normal average rate of climb), SAMI personnel inquired about the state of the subjects and asked the current reading of $SpO_2$ in their respective pulse oximeters. Subjects felt either hypoxia symptoms or were instructed by the flight controller from the air traffic control station about their low levels of oxygen, at that time subjected were instructed to don their masks (with 100% oxygen) by removing first their headsets, while being aided by the support staff inside the chamber.

SAMI safety procedures recommended that SACs hypobaric exposure should not go above 22,000 ft. When the SAMI personnel observed hypoxia signs or symptoms, subjects were asked to don their oxygen mask and breathe 100% to correct their hypoxic state. Lastly, subjects were provided a 30 minutes post-flight review of flight video, oxygen saturation levels, and sensations during their flight training in the hypobaric chamber.

### E. Data Collection

Data collection was conducted during 4 research campaigns at SAMI. The first two campaigns occurred simultaneously in October 2015, the third campaign was 6 months after the first two, and the fourth campaign took place 6 months after the third one.

Vital signs and physiological variables (HR, BR, T, SP, DP, MAP, $SpO_2$) were recorded for each participant using the ZB wearables for 10 minutes before and after each hypobaric run, ZB devices were not allowed inside the chamber because they are powered by lithium batteries. $SpO_2$ and HR were always measured and monitored when the participants were inside the chamber while SAMI support personnel recorded both the number of desaturations and duration of each desaturation.

SAMI personnel recorded relevant data from the flight profile inside the hypobaric chamber from about 9,000 ft – 10,000 ft during the ascent to about 17,000 – 20,000 ft during the descent and after having donned the oxygen mask. This is the range in altitude where subject's physiology started being affected. Flight duration ranged from about 8.5 min to about 13.5 min inside the chamber. Data collection was done by extracting from the recorded video the time, altitude and oxygen desaturation level, every 30 seconds in order to plot an oxygen desaturation pressure curve for each subject (measured), and then compare it with the calculated (theoretical) oxygen desaturation pressure curve [5], [6]:

$$SO_2\,(\%) = 100 \cdot \left( \left( 23400 \cdot \left( PO_2{}^3 + 150 \cdot PO_2 \right)^{-1} \right) + 1 \right)^{-1} \quad (1)$$

This is referred to as the Severinghaus modified existing curve (previously by [14]) in 1979, which represents a more accurate expression than the previous Hill expression [14]. The partial pressure of oxygen was obtained using the following expression for every altitude point:

$$PO_2(kPa) = 101.325 \cdot \left(1 - 6.87535 \cdot 10^{-6} \cdot Alt(ft)\right)^{5.2561} \quad (2)$$

where the pressure is given in kPa and the altitude in feet. Altitude was obtained from the video-recorded flight data, then use to obtain $PO_2$ in (2). Then, the value obtained in (2) was used in (1) to obtain $SO_2$ (%).

### III. Results

Study subjects ranged between 23 and 58 years old with a mean age of 34.75 with a SD of 9.37 years (34.8 ± 9.4). Out of 18 subjects, 16 were male (89%) and two females.

Among the 18 subjects, 90% of these were not taking any medication, 5% were taking only multivitamins and the other 5% were taking analgesics or allergy pills. PoSSUM campaigns occurred twice a year, during October and during March (strong allergy season in Daytona Beach, Florida). Only 10% of subjects stated they were current smokers and 50% of the subjects said they consume alcohol between two times and six times a week. 15% of subjects stated they had some sort of oral surgery and 25% had other associated surgeries relating their knee, back, hips, shoulder or neck. Only 7.5% of subjects indicated they had some sort of gastrointestinal issues in the past, and although this number represents only 3 subjects among the 18 subjects, we will see later that the gastrointestinal score is one of the variables most affected in subjects.

About 11% of the SACs started experiencing their first symptoms at about 11,000 ft and were not allowed to fly higher than FL170 or FL180 per SAMI personnel safety decisions (who were constantly monitoring SACs vitals during their flight inside the hypobaric chamber. Participants were answering SAMI's questions verbally), at that time they were told to don their masks. About 78% of SACs started to feel first symptoms between 15,000 ft and 18,000 ft, second symptoms at about 20,000 ft and third symptoms at about 21,500 ft. SACs donned their masks when they recognized their third symptoms. Some participants had to don their masks about 20,000 ft. Only 2 participants (11% of participants) did not develop several symptoms, but they were asked to don their mask at about FL220 to avoid high altitude cabin depressurization [24]. Recovery was very fast and within 30 seconds to 1 minute of donning their mask, SACs recovered their normal state without any hypoxia symptoms. SACs recovered most of their cognitive skills after oxygen mask was donned.

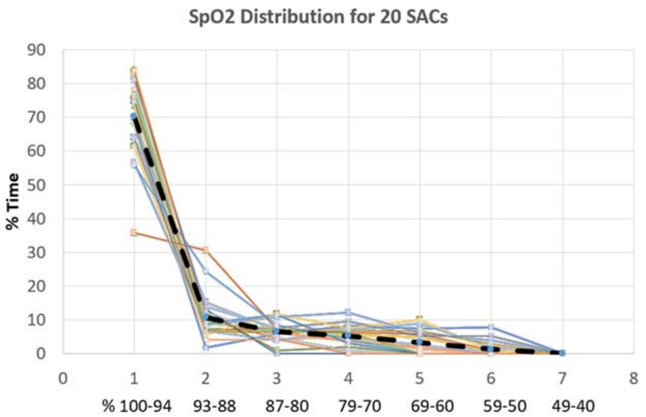



Fig. 1 Oxygen saturation ($SpO_2$) level and their corresponding time at that level for 20 subjects. Dashed line represents the average of all data

Results (Fig. 1) indicate that all 18 SACS spent about 70.2% of the time at 100-94% $SpO_2$ with a total of 5 desaturations, followed by 10.6% of the time with 56 desaturations at 93-88% $SpO_2$, followed by 6.6% of the time with 45 desaturations at 87-80% $SpO_2$, followed by 5.3% of the time with 37 desaturations at 79-70% $SpO_2$, followed by 3.3% of the time with 22 desaturations at 69-60% $SpO_2$, followed by 1.2% of the time with 11 desaturations at 59-50% $SpO_2$. None of the SACs spent any time or had any desaturations at 49-40% $SpO_2$. Fig. 1 shows the $SpO_2$ distribution for all 18 SACs. The solid dash line indicates the average time for each level of desaturation. The lowest $SpO_2$ among all SACs is 66.7% with a SD of 10.9%, and the mean $SpO_2$ is 93.2% with a SD of 2.7%. All SACs had a maximum $SpO_2$ of 99%. Fig. 2 displays the individual $SpO_2$ distribution for the subjects.

#### *A. Hypobaric Chamber Analysis*

The average of the highest PR among the 20 SACs is 114.95 bpm with a SD of 17.96. The average of the lowest PR is 59.6 bpm with a SD of 11.64, and 88.40 with a SD of 16.23 for the average of the mean PR.

Fig. 3 shows the oxygen desaturation pressure curves (measured and calculated) for each participant. The measured data (every 30 seconds) are portrayed in orange with every data point as a square, and the calculated data are given in grey (data point is triangle). The blue dashed line corresponds to the polynomial fit ($6^{th}$ order) of the measured oxygen with the pulse oximeter. Table I provides the coefficients for each of the polynomial fit and the correlation coefficient.

From the above analysis, we suggest two main groups during hypobaric exposure. The first group is subjects 3, 4, 5, 7, 8, 10, 12, 13, 14, 15 and 17; second group is subjects 1, 2, 6, 9, 11, 16, and 18. These groups were analyzed by inspecting the polynomial coefficients. We took an average of each of the above polynomial coefficients for each group so that the polynomial fit has the form:

$$y1 = (0.00115)x^6 + (-0.037)x^5 + (-0.4668)x^4 + (-2.9487)x^3 + (9.5294)x^2 + (-14.4397)x + 104.334 \quad (3)$$

with a correlation coefficient of 0.9808. x and y are the pressure and oxygen desaturation, respectively. For this group (3), coefficients A, E, G > 0 and B, C, D, F < 0. Similarly, the second group (4) during exposure adopts a form given by the following polynomial:

$$y2 = (-0.00016)x^6 + (0.008257)x^5 + (-0.15603)x^4 + (1.4112)x^3 + (-6.2164)x^2 + (11.9774)x + 90.3036 \quad (4)$$

with a correlation coefficient R= 0.9799, with B, D, F, G > 0 and A, C, E < 0. We can label the above two polynomials Type I-exposure (3) and Type II-exposure (4) since they have different coefficients. Similarly, we obtained two other polynomials during recovery phase. The first one (5) follows the form:

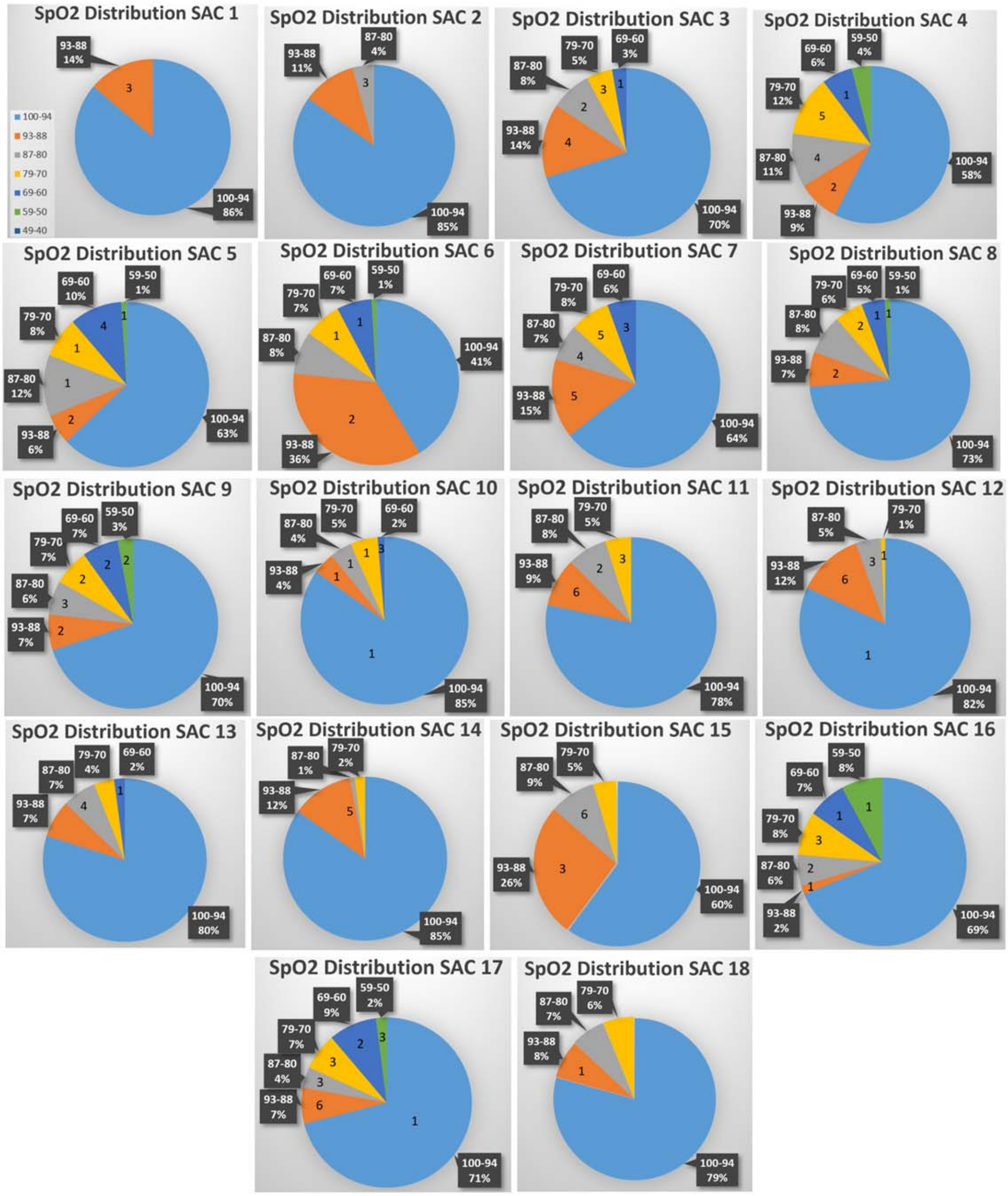



Fig. 2 Oxygen saturation distribution for 18 subjects

$$y1 = (0.127264)x^5 + (-2.7727)x^4 + (23.5103)x^3 + (-96.4506)x^2 + (190.7413)x - 36.0975 \quad (5)$$

with R = 0.9944; B, D, F > 0, and C, E, G < 0, and the second polynomial (6) follows the form:

$$y2 = (-0.00037)x^5 + (-0.02677)x^4 + (4.7902)x^3 + (-16.0136)x^2 + (82.1986)x + 66.9366 \quad (6)$$

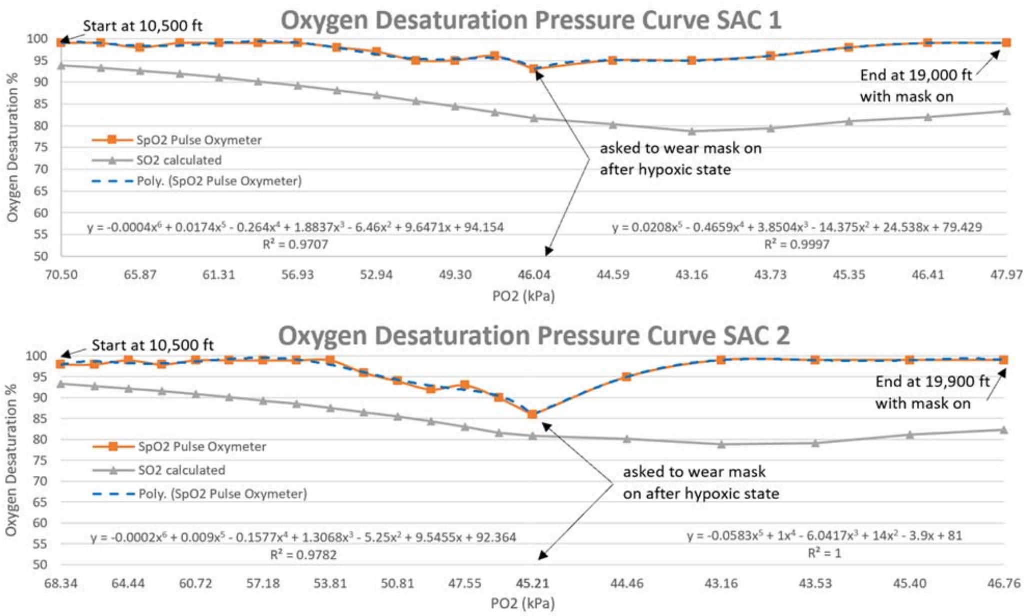
with R = 0.952; B, C, E < 0, and D, F, G < 0. The first polynomial for the recovery phase (Type I-recovery) corresponds to subjects 1, 3, 5, 6, 7, 8, 9, 10, 11, 14 and 15. The second polynomial for the recovery phase (Type II-recovery) corresponds to subjects 2, 4, 12, 13, 16, 17 and 18.

TABLE I A
POLYNOMIAL FIT OF OBSERVED SPO2 DURING EXPOSURE
$y = Ax^6 + Bx^5 + Cx^4 + Dx^3 + Ex^2 + Fx + G$,
0 < R = CORRELATION COEFFICIENT < 1

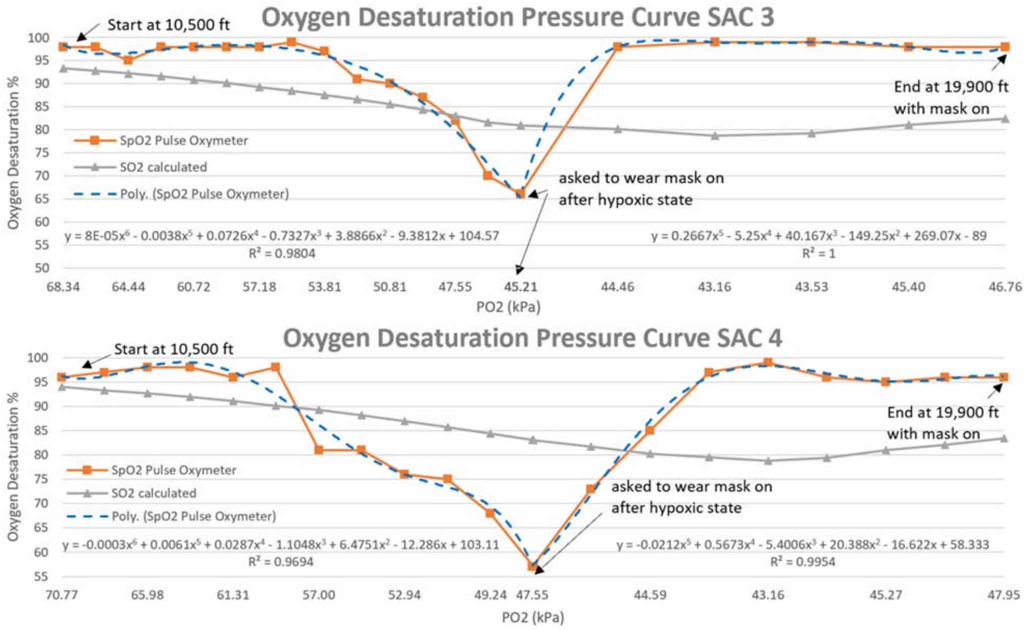
| A | B | C | D | E | F | G | R |
|---|---|---|---|---|---|---|---|
| -0.0004 | 0.0174 | -0.264 | 1.8837 | -6.46 | 9.6471 | 94.154 | 0.97 |
| -0.0002 | 0.009 | -0.1577 | 1.3068 | -5.25 | 9.5455 | 92.364 | 0.97 |
| 0.00008 | -0.0038 | 0.0726 | -0.7327 | 3.8866 | -9.3812 | 104.57 | 0.98 |
| -0.0003 | 0.0061 | 0.0287 | -1.1048 | 6.4751 | -12.286 | 103.11 | 0.96 |
| -0.00001 | 0.0004 | -0.0046 | -0.0019 | 0.0852 | -0.7818 | 99.511 | 0.98 |
| 0.0001 | -0.0018 | -0.0348 | 0.9319 | -6.4188 | 14.401 | 89.056 | 0.95 |
| 0.00004 | -0.0017 | 0.0257 | -0.231 | 1.3553 | -4.3017 | 101.59 | 0.98 |
| 0.00005 | -0.003 | 0.0669 | -0.763 | 4.298 | -10.077 | 103.19 | 0.99 |
| -0.0003 | 0.0133 | -0.2522 | 2.2605 | -9.7004 | 17.927 | 87.431 | 0.99 |
| 0.0003 | -0.0151 | 0.2444 | -1.8512 | 6.7433 | -11 | 103.99 | 0.98 |
| -0.0002 | 0.0113 | -0.2187 | 2.0355 | -9.1197 | 17.318 | 85.948 | 0.97 |
| 0.0011 | -0.0396 | 0.5609 | -3.79 | 12.266 | -16.454 | 102.64 | 0.98 |
| 0.00001 | -0.0008 | 0.0205 | -0.2394 | 1.3249 | -3.1353 | 100.26 | 0.98 |
| 0.0022 | -0.0664 | 0.7791 | -4.3892 | 12.088 | -14.542 | 103.17 | 0.99 |
| 0.0092 | -0.2834 | 3.3383 | -19.091 | 54.959 | -74.343 | 129.43 | 0.93 |
| -0.00002 | 0.0017 | -0.0395 | 0.3738 | -1.9475 | 5.9451 | 90.872 | 0.99 |
| 0.00001 | -0.0008 | 0.00207 | -0.2413 | 1.3415 | -2.5347 | 96.223 | 0.98 |
| -0.0001 | 0.0069 | -0.1253 | 1.0859 | -4.6181 | 9.0582 | 92.3 | 0.99 |

TABLE I B
POLYNOMIAL FIT OF OBSERVED SPO2 DURING RECOVERY
$y = Bx^5 + Cx^4 + Dx^3 + Ex^2 + Fx + G$,
0 < R = CORRELATION COEFFICIENT < 1

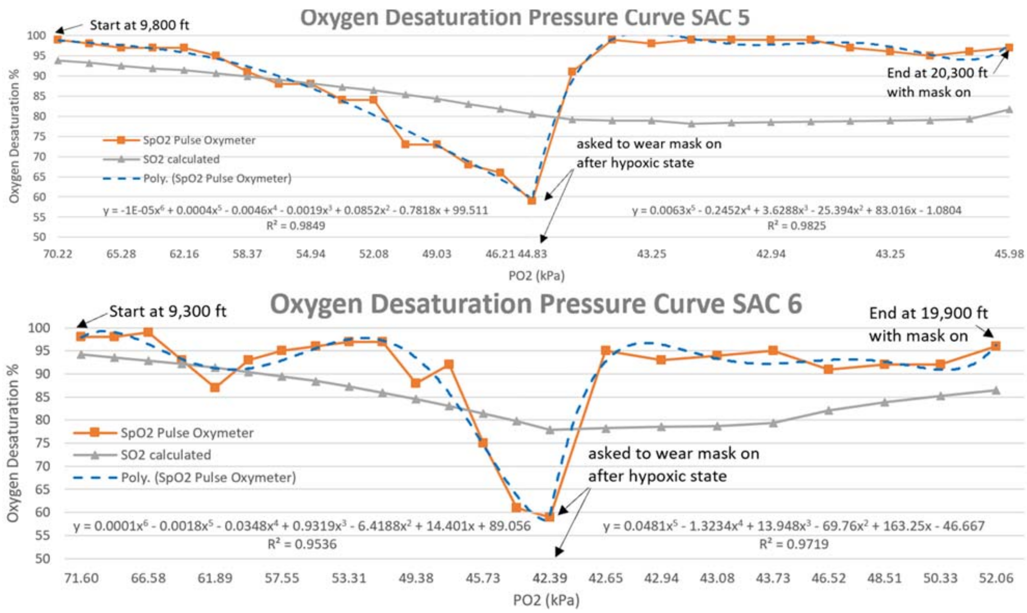
| B | C | D | E | F | G | R |
|---|---|---|---|---|---|---|
| 0.0208 | -0.4659 | 3.8504 | - 14.375 | 24.538 | -2.825 | 0.99 |
| -0.0583 | 1 | - 6.0417 | 14 | 3.9 | 81 | 1 |
| 0.2667 | -5.25 | 40.167 | -149.25 | 269.07 | 89 | 1 |
| 0.0212 | 0.5673 | - 5.4006 | 20.388 | 16.622 | 58.333 | 0.99 |
| 0.0063 | -0.2452 | 3.6288 | -25.394 | 83.016 | - 1.0804 | 0.98 |
| 0.0481 | - 1.3234 | 13.948 | -69.76 | 163.25 | -46.667 | 0.97 |
| 0.0631 | -1.7057 | 17.687 | -86.551 | 195.08 | -62.5 | 0.99 |
| 0.0532 | -1.4674 | 15.457 | -77.167 | 180.52 | -59 | 0.98 |
| 0 | -2.4167 | 32.667 | - 158.58 | 326.33 | -143 | 1 |
| 0 | 0 | 4.1667 | - 39 | 117.83 | 16 | 1 |
| 0.225 | -4.25 | 31.208 | -112.25 | 200.07 | - 45 | 1 |
| 0.0356 | -0.9468 | 9.5508 | -45.504 | 102.21 | 11.75 | 0.78 |
| 0 | -1.8333 | 24.667 | -119.17 | 244.33 | 82 | 1 |
| 0.25 | -4.5417 | 32 | -109.96 | 185.25 | -24 | 1 |
| 0.4667 | -8.8333 | 63.833 | -218.67 | 353.2 | -118 | 1 |
| -0.0044 | 0.0843 | -0.0949 | -6.9857 | 47.077 | 12.067 | 0.97 |
| -0.0335 | 0.9914 | -10.735 | 50.218 | -86.023 | 101.6 | 0.98 |
| 0.0004 | -0.0503 | 1.1755 | -10.903 | 43.931 | 35.533 | 0.98 |



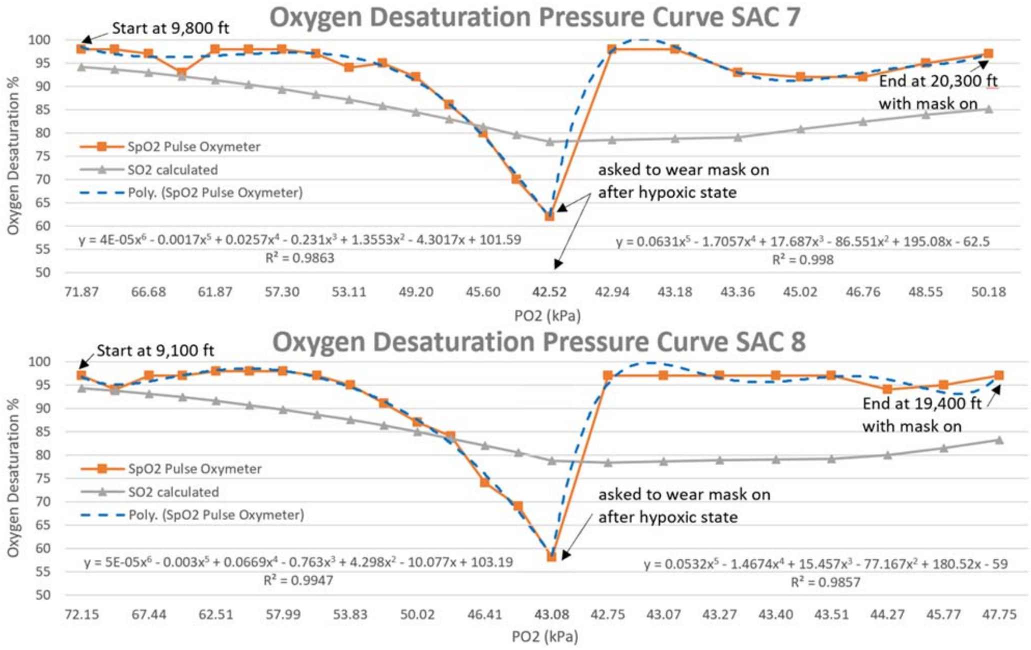

(a) Oxygen desaturation curves for subjects 1 and 2



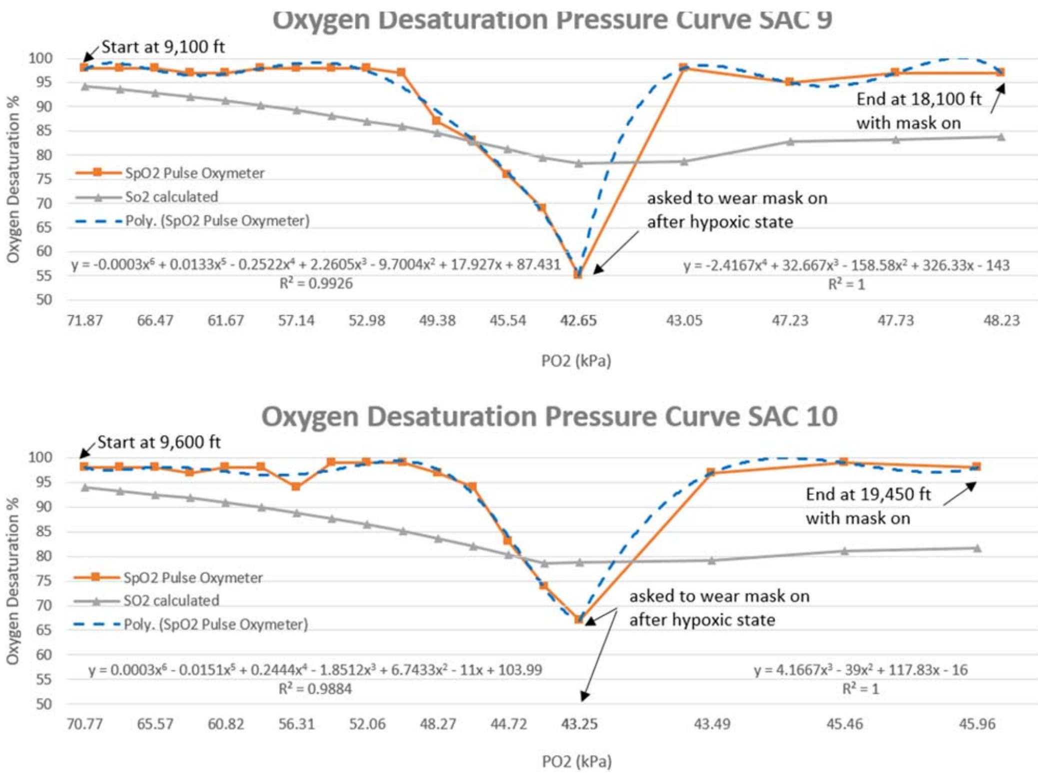

(b) Oxygen desaturation curves for subjects 3 and 4



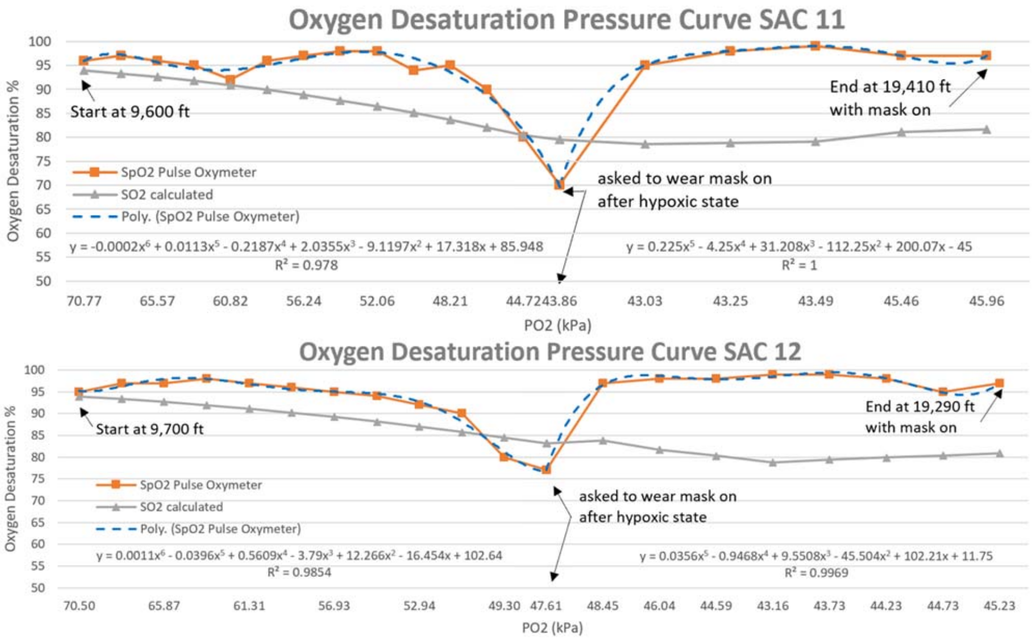

(c) Oxygen desaturation curves for subjects 5 and 6



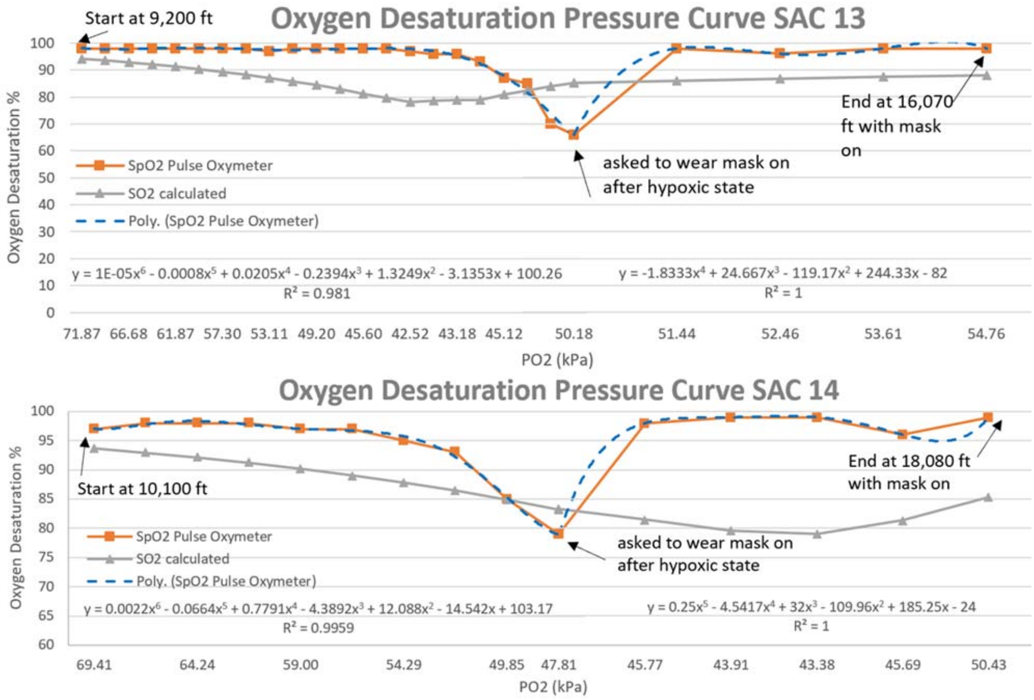

(d) Oxygen desaturation curves for subjects 7 and 8



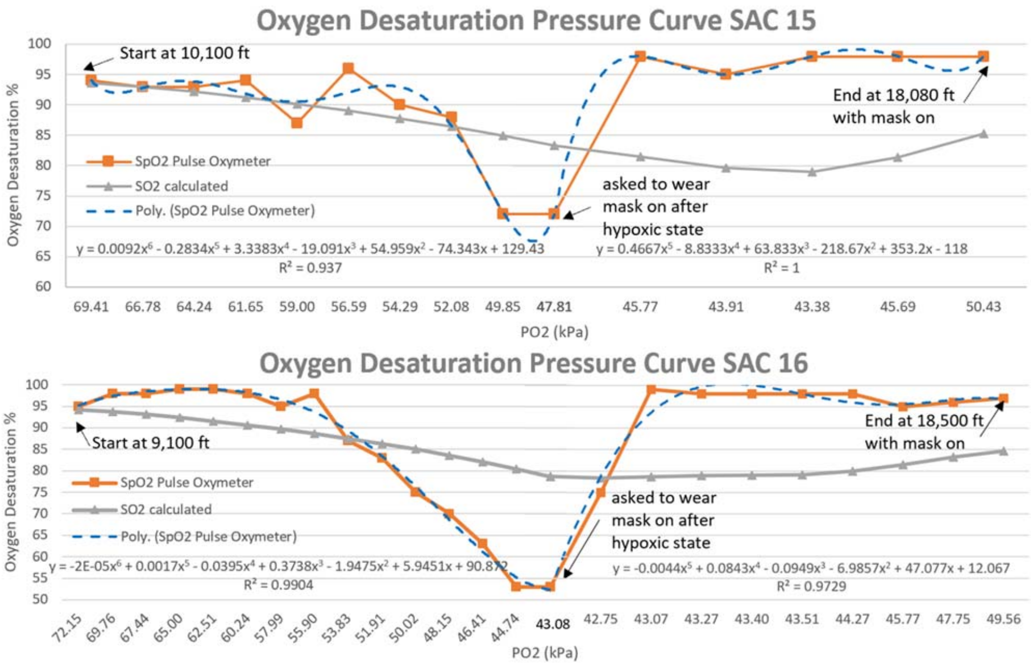

(e) Oxygen desaturation curves for subjects 9 and 10



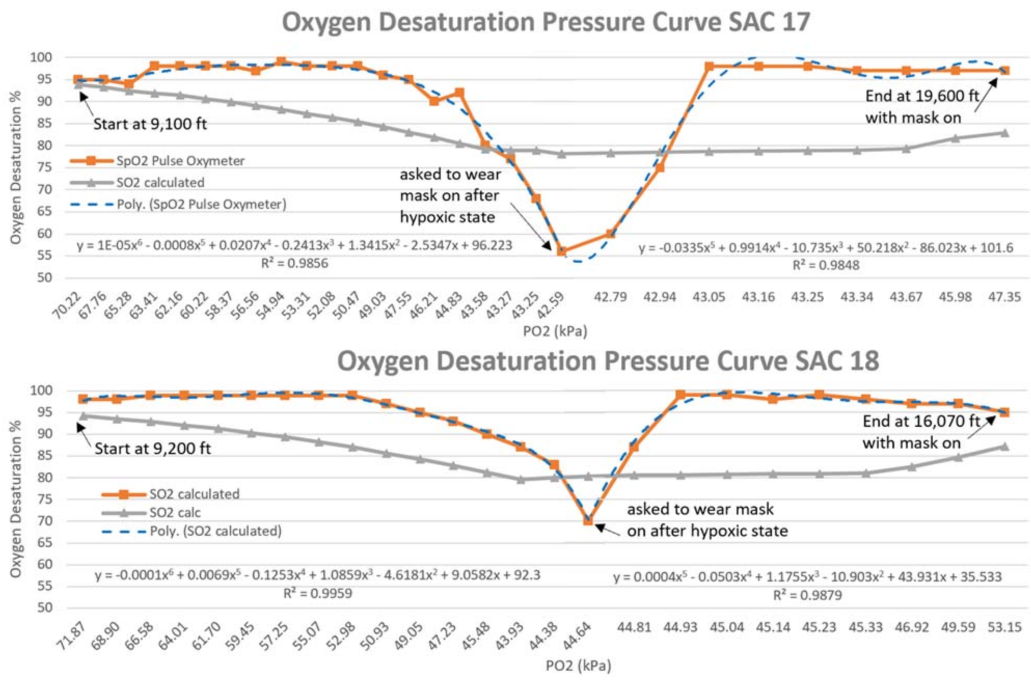

(f) Oxygen desaturation curves for subjects 11 and 12




(g) Oxygen desaturation curves for subjects 13 and 14




(h) Oxygen desaturation curves for subjects 15 and 16




(i) Oxygen desaturation curves for subjects 17 and 18

Fig. 3 Oximeter desaturation pressure curves (measured and calculated) for 18 subjects

Participants experienced several desaturations during their hypobaric chamber training as depicted in Fig. 4. Most of these desaturations are negligible in terms of oxygen desaturation percentage and duration; however, we highlight the main desaturation(s) for each subject (Fig. 3). Subjects 1 and 2 are displayed in Fig. 3 (a), subjects 3 and 4 are shown in Fig. 3 (b), subjects 5 and 6 are depicted in Fig. 3 (c), subjects 7 and 8 are presented in Fig. 3 (d), subjects 9 and 10 are displayed in Fig. 3 (e), subjects 11 and 12 are shown in Fig. 3 (f), subjects 13 and 14 are depicted in Fig. 3 (g), subjects 15 and 16 are presented in Fig. 3 (h), and subjects 17 and 18 are shown in Fig. 3 (i). Subject 1 experienced no major desaturations. Subject 2 experienced a desaturation at 86%, 129 bpm for five seconds (contrast against graph for SAC 2). Subject 3 registered a main desaturation at 66%, 120 bpm, for five seconds. Subject 4 had a desaturation at 57%, 106 bpm for five seconds. Subject 5 experienced a desaturation at 59%, 117 bpm for 5 seconds. Subject 6 showed a $SatO_2$ at 59%, 47 bpm for ten seconds.

Subject 7 had a desaturation at 62%, 92 bpm for five seconds. Subject 8 experienced a desaturation at 58%, 61 bpm for five seconds. Subject 9 had a desaturation at 55%, 120 bpm for five seconds. Subject 10 experienced a desaturation at 67%, 99 bpm for five seconds. Subject 11 experienced two main desaturations: first at 80%, 105 bpm; second at 70%, 111 bpm for five seconds each. Subject 12 had a desaturation at 77%, 119 bpm for five seconds. Subject 13 registered a main desaturation at 66%, 117 bpm, for five seconds. Subject 14 experienced a desaturation at 79%, 99 bpm, for five seconds. Subject 15 had a $SatO_2$ at 72%, 143 bpm, for five seconds. Subject 16 had a main desaturation at 53%, 111 bpm, for 20 seconds. Subject 17 registered a main desaturation at 56%, 139 bpm, for five seconds. Finally, subject 18 experienced a $SatO_2$at 70%, 139 bpm, for five seconds.

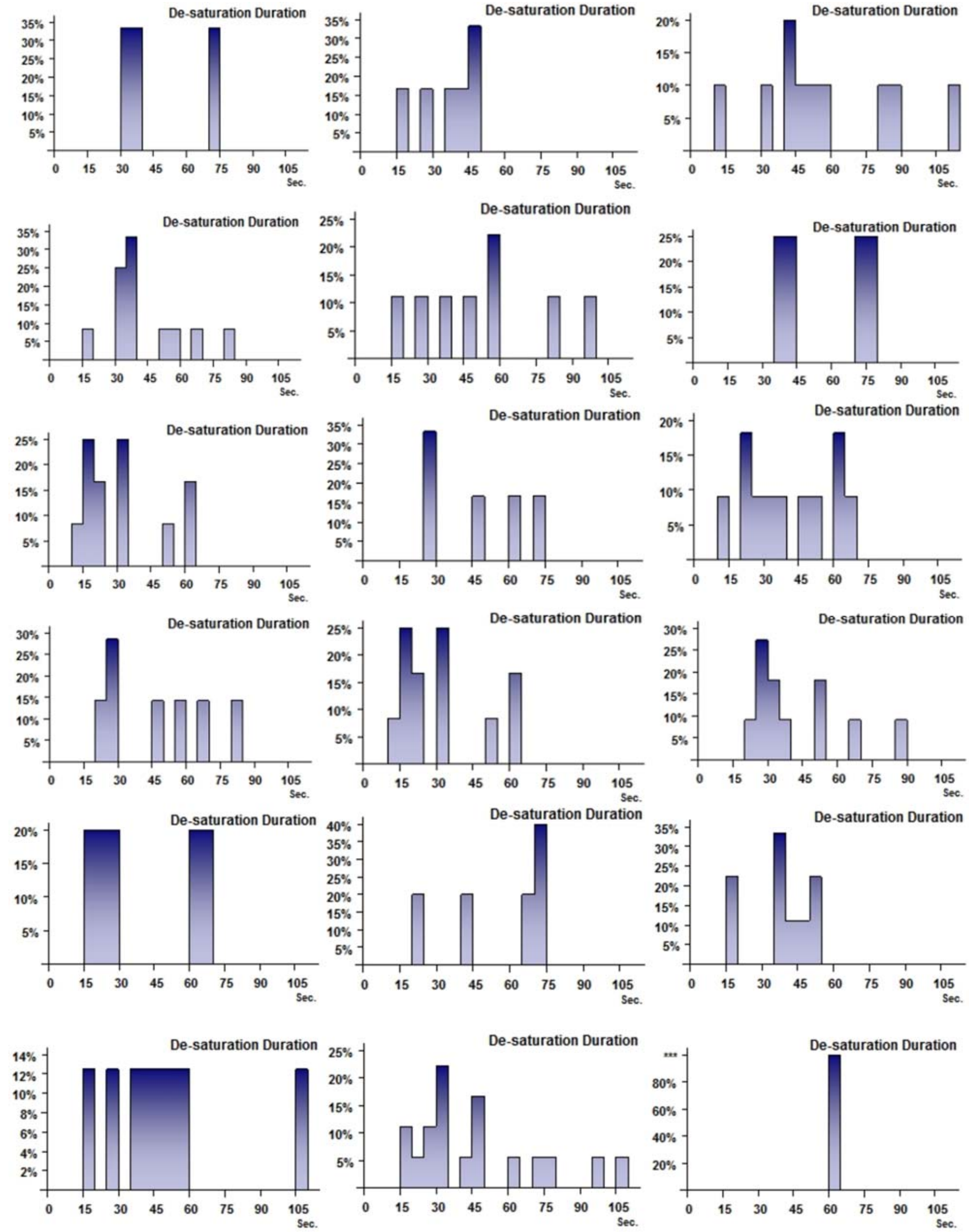



Fig. 4 Oxygen saturation and number of desaturations for 18 subjects

Fig. 4 shows the number of desaturations for each subject. For example, SAC 1 only experienced 3 desaturations as indicated in the middle of the slice, which occurred between 93% – 88% (see Fig. 2).

During this study, several symptoms were identified in all 40 SACs. It is important to highlight that before reaching 18,000 ft all participants had reported at least the first hypoxia symptom. The two most common symptoms experienced by the participants were SP, especially temperature related (hot or cold sensation), and concentration deficit (Fig. 5). This temperature feeling [4] occurred in face and hands mainly, while the concentration deficit meant that the SAC had a hard time to focus on the given task, or had some type of visual tracking scan deficit that made subjects spend more effort to scan and made given inputs by the air traffic control station, or loss control of the joystick, or had a hard time remembering some of the commands given by the SAMI crew. These two symptoms were experienced by 65.0% and 52.5% of the participants, respectively. The next three common symptoms SACs experienced were light-headed, tingling and nausea feeling by 32.5%, 27.5% and 25.0% of the participants, respectively. The third set of symptoms, such as grainy and tunnel vision, ears pressure or pounding, and increased HR feeling and palpitations were also experienced by 20.0%, 20.0%, and 12.5% of the participants, respectively. Finally, other symptoms were also experienced by a few SACs. Example of these symptoms were numbness in the lips and fingers that prevented the participants to articulate properly as is reflected in their speech being difficult for communication with SAMI personnel, changes in breathing, and general psychomotor symptoms which could have affected the manipulation of the joystick as they were flying the simulator inside the hypobaric chamber. These last three symptoms resulted in 10.0%, 10.0%, and 17.5%, respectively.

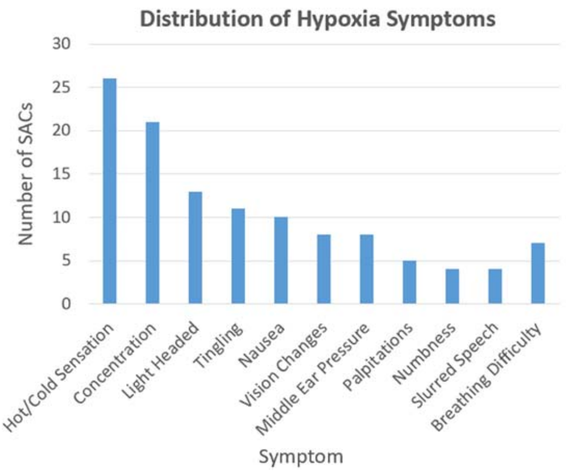



Fig. 5 Hypoxia symptoms for 40 subjects

Numerous antecedents in HH research used validated AMS scales for collecting HH symptoms, but the myriad of symptoms observed during this study, and their distribution and presentation among this group of SACs, advises for an open list of sensorial perceptions rather than the few included in the mentioned AMS scales.

## IV. Discussion

Previous studies [18] spatial memory impairment and neurodegeneration reported on the downregulation of the brain caused by repeated HH exposure.

This research study dealt with 40 subjects being exposed to and hypobaric environment for a short period (order of a few minutes) as part of a training for prospective participants in suborbital operations. A pulse oximeter device monitored the level of oxygen desaturation for each subject during flight in the hypobaric chamber. These devices tracked these variables for most of the subjects. However, there were a few instances where the data were noisy or missing, perhaps due in part to a motion artifact or subject movement while flying the simulator inside the hypobaric chamber. Because of the previously described safety issues, Bioharness instrumentation cannot go inside the chamber during flights, which prevented researchers to gather valuable HR, BR and other physiological parameters inside the chamber and any correlation among these parameters. However, the use of the pulse oximeter allowed us to at least gather the HR data while inside of the chamber.

Motion artifact or subject improper movement when wearing the pulse oximeter while subjects were in the hypobaric chamber may have been a contributing factor to inaccuracies in the oxygen desaturation for at least one subject, which does not significantly affect the behavior of the average curve (for 20 subjects) representing the oxygen desaturation and time spent within each percentage bracket (e.g. 100%-94% to 49%-40%). Motion artifact could have been the main cause why some data were missing when using the Bioharness. In the end, we gathered complete data set for 12 subjects, which was analyzed.

In our study, as observed in Fig. 1, all subjects spent an average of 70% of their time with an oxygen saturation level of between 94% to 100%, and about 17% of their time with oxygen saturation levels between 80% and 93%; about 5% between 70% and 79% and about 4.5% between 50% and 69%. It is important to note that one subject spent only about 35% between 94% and 100% blood oxygen saturation levels, which was probably an artifact leading to an inconsistent measurement, given the subject's clinical features and cognitive function during the exposure were unaffected. Neglecting this subject, the average time spent between 94% and 100% would be only 2% higher, and 0.5% higher between 88% and 93%, which suggests that these are very small variations. For the rest and lower of the saturation levels, the difference would be less than 0.1%. This means that the dashed line would be shifted slightly higher these amounts. Thus, this single data point (if considered an outlier) does not affect the black dashed line significantly. These results are in concordance with previous HH research [28] and physiologic models predicting that altitudes up to 25,000 ft produce blood oxygen desaturation readings in the ranges observed during the present study and modeled by classic physiology works about oxyhemoglobin and $PO_2$. Oxygen saturation [16] is a critical physiological parameter to identify and evaluate preflight and post flight. Prospective commercial spaceflight ventures will fly participants with smoking history who may be more sensitive to cabin pressure and $O_2$ levels variations [21]. The Aerospace Medical Association (AsMA) assumes that the cabin will be pressurized to sea level (760 mmHg) with 80% nitrogen, 20% oxygen atmosphere, and that no life support system would be necessary for nominal flights [30].

This means, that there is no requirement for special life support equipment, and in the event of off-nominal or contingencies scenarios or emergency (e.g. cabin decompression or fumes in the cabin) proper measures would need to be considered for these critical spaceflight operations, such as donning an oxygen mask may be necessary.

Several important observations can be extracted from this study (Fig. 3) based on the polynomial fit of order 6th between the oxygen saturation percentage of all subjects and the associated pressure curve when in the hypobaric chamber.

Among the 18 subjects analyzed, we first observed that only two subjects experienced oxygen saturation levels higher than their associated oxygen saturation levels calculated with theoretical curves [6], from (1). Although these curves represent higher oxygen saturation levels, they both show a similar behavior with a decrease in their levels of oxygen (from 98%) saturation as they approach their hypoxic state with 93% and 88% oxygen saturation being these their minimum. Immediately after donning their masks on, their normal oxygen saturation levels (98%) were retrieved after one minute. This variation in performance can be explained by individual differences such as exercise habits, previous HH exposure or cardiovascular epigenetics, just to mention a few confounding factors.

The second important observation is that the next 16 subjects have oxygen saturation pressure curves with a more pronounced behavior. All these subjects experienced slightly different experimental curves, each curve started with a plateau of their oxygen saturation levels, and it decreased or slightly increased momentarily before decreasing again. Depending on the subject, this $SpO_2$ decrease varied from about three to about five minutes before their $SpO_2$ went below their theoretical value obtained from (1). Subjects experienced lower $SpO_2$ than their theoretical values for about one minute to three minutes. At this point, subjects were told they had reached a hypoxic state and asked to don their oxygen masks on. With masks on, half of the subjects took as low as thirty seconds, and the rest of the subjects took between sixty and ninety seconds to retrieve their normal $SpO_2$ (about 97%-99%). This $SpO_2$ did not remain constant, but instead it dropped as much as 2%-4% ($SpO_2$ about 92%-95%) for some subjects, then it slightly increased again. These slight oscillations were observed in most if not all the subjects with varying time length. The shape of the $SpO_2$ curve for these 16 subjects showed a performance below expected, this deficit should be explained by the same confounding factors described above, but also showed a consistent pattern that led to the third observation.

The third observation was obtained after analyzing the $SpO_2$ plots and realizing that graphs of data collected from the hypobaric chamber was used to provide a preliminary model of the oxygen desaturation and pressure curve for each subject, as explained earlier in the hypobaric chamber analysis section. Although this analysis was only provided for 18 subjects, data suggest that a polynomial of sixth order could be initially used to predict future physiology and performance behavior in a subject while conducting similar tasks in the hypobaric chamber. From our data, it is suggested that a polynomial of sixth order with various polynomial coefficients could be used during exposure since 61% of subjects follow Type I-exposure polynomial fit and the rest of subjects follow a sixth-order Type 2-exposure polynomial fit. During recovery, data suggest that 61% of subjects follow a fifth-order Type 1-recovery polynomial fit, and the rest of subjects follow a fifth-order Type 2-recovery polynomial fit. More subjects will be required to further optimize the nature of the polynomial that fits the experimental (oxygen desaturation) data.

Analyzing the distribution of all the symptoms experienced and reported by all 40 subjects, three main groups can be extracted. The first group (> 50%-55% of subjects experienced these symptoms) includes the two most frequent symptoms as reported by previous research, such as cold or warm flashes [9], [10] in their chest or face and difficulty on concentrating in the task conducted in the chamber. The second group (> 20%-25% of subjects experienced these symptoms) includes lightheadedness, tingling in the subject's hands, dizziness/ nausea and vision issues while conducting the task. The last group (< 13% of subjects experienced these symptoms) includes other minor symptoms, such as pressure in the ears, HR variability, speech or communication problems and breathing issues among a minority of the participants.

The real-time reporting and recording of HH symptoms carried during the present study allowed researchers to collect and analyze very granular data related to not only the type of symptoms, but also time of onset and cumulative symptoms during the whole extent of the hypobaric session. This procedure allowed better analysis and discussion of perceptions related to HH and prevented data loss due to expected memory deficits during the HH exposure. This might be important for other HH training programs where the subjects are asked to remember and report their symptoms after the hypobaric session. Also, for training programs using AMS scales for HH symptoms assessing, these results might suggest that those validated scales might disregard some other symptoms and may not be the best fit for HH training.

## V. Conclusion

HH is a major stress factor associated with physiological alterations. This study has shown that a heterogeneous group of subjects under physiological stressors such as HH presented known signs and symptoms directly relatable to oxygen deprivation, leading to impairments in superior cognitive function, which is one of the most important requirements for safe flight operations. After a standard HH exposure, the participants of this study showed predictable affectations described by previous research [3], [7], [11], [14], [28], [31] and modeled by traditional and widely accepted respiratory physiology models. Furthermore, the observations and analysis from this research demonstrated the insidious and fully reversible onset of HH signs and symptoms depending directly on $PO_2$, $SpO_2$ variations, and the individual variables affecting this relationship. Real-time reporting and recording of HH symptoms described in this research evidenced SP and task focusing as the earliest and most common indicators; the SAC group participating in this study reported a diverse inventory of sensations and perceptions concurring around known and recognized warning signs that might alert individuals exposed to mild and moderate HH.

A 6th order polynomial fit indicates that predicted $SpO_2$ and observed $SpO_2$ curves for this group of individuals present very similar behavior between subjects during a standard HH exposure, suggesting a predictive model of $SpO_2$ during hypoxia, such a model should be tested and refined by further research that might be able to project this model as a major performance moderator in hypoxia and hypobaric activities.

Due to the high relevance of HH as a potential human performance hazard affecting the safety of aerospace operations, hypoxia training is an effective practice aiming to mitigate preventable operational risks. This assessment of HH signs and symptoms reveals that hypoxia training on SACs retrieved comparable physiologic results and reported symptomatology to previous HH research performed in homogeneous aviator populations, and allowed researchers to propose a modeling function for predicting human performance in terms of blood oxygen saturation and altitude exposure, that might contribute to prevent cognitive dysfunction in safety-critical activities.

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