Flight Performance During Exposure to Acute Hypobaric Hypoxia

Yuval Steinman; Marieke H. A. H. van den Oord; Monique H. W. Frings-Dresen; Judith K. Sluiter

INTRODUCTION: The purpose of the present study was to examine the influence of hypobaric hypoxia (HH) on a pilot's flight performance during exposure to simulated altitudes of 91, 3048, and 4572 m (300, 10,000, and 15,000 ft) and to monitor the pilot's physiological reactions.

METHOD: In a single-blinded counter-balanced design, 12 male pilots were exposed to HH while flying in a flight simulator that had been placed in a hypobaric chamber. Flight performance of the pilots, pilot's alertness level, S_pO_2, heart rate (HR), minute ventilation (V_E), and breathing frequency (BF) were measured.

RESULTS: A significant difference was found in Flight Profile Accuracy (FPA) between the three altitudes. Post hoc analysis showed no significant difference in performance between 91 m and 3048 m. A trend was observed at 4572 m, suggesting a decrease in flight performance at that altitude. Significantly lower alertness levels were observed at the start of the flight at 4572 m compared to 91 m, and at the end of the flight at 4572 m compared to the start at that altitude. S_pO_2 and BF decreased, and HR increased significantly with altitude.

DISCUSSION: The present study did not provide decisive evidence for a decrease in flight performance during exposure to simulated altitudes of 3048 and 4572 m. However, large interindividual variation in pilots' flight performance combined with a gradual decrease in alertness levels observed in the present study puts into question the ability of pilots to safely fly an aircraft while exposed to these altitudes without supplemental oxygen.

KEYWORDS: flight performance, Stanford Sleepiness Scale, pilots, alertness levels, hypobaric hypoxia.

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During flight, the ability of a pilot to maintain high cognitive and psychomotor performance is essential for flight safety. In aviation, altitudes up to 3048 m (10,000 ft) are regarded as a physiological zone where the impact of hypoxia on the pilot's cognitive and psychomotor performance is relatively small and, therefore, has few implications on flight safety.[9,21] However, a study done by the Australian army reported that 87% of the nonpilot aircrew and 61% of the pilots operating at altitudes up to 3048 m experienced one or more symptoms of hypoxia.[24] In addition, there is accumulating data regarding hypoxia-related incidents in military forces at altitudes lower than 3048 m.[5,7]

Over the years, extensive research has been done to assess the effect of hypoxia on cognitive performance. In pilots, hypoxia has been shown to impair working memory[16] and influence the ability to process information.[3] In addition, studies performed with nonpilots as subjects show that hypoxia may impair complex decision making,[14] and increase reaction time and decision errors.[6] However, although these tests were designed to assess those skills considered important for a pilot's ability to fly and control an aircraft, it is hard to deduce from the results what the exact effect of hypoxia will be on the pilot's ability to control the aircraft and perform aviation-specific tasks such as takeoff, level flight, air maneuvers, landing, etc.[20]

There are limited data regarding the impact of hypoxia on the pilot's ability to fly and control an aircraft. Hypoxia studies

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performed using a flight simulator reported a significant decrease in flight performance at 4572 m (15,000 ft) compared to baseline,[8] significantly more procedural errors being made, especially during descent and landing,[17] and higher variability in flight performance during hypoxia exposure of 5486 m (18,000 ft).[26]

In the above-mentioned flight performance studies, hypoxic conditions were achieved by altering the oxygen fraction in the inhaled air without changing barometric pressure, resulting in normobaric hypoxia (NH). Another method used for reaching hypoxic conditions is to lower the barometric pressure, resulting in hypobaric hypoxia (HH). The common way of thinking is that if in both HH and NH the decrease in inspired partial pressure of oxygen was the same, the cardiorespiratory response would be the same. However, there is accumulating evidence suggesting that the decrease in barometric pressure experienced in HH induces different physiological responses compared to NH.[15,22,27] Studies have shown higher breathing frequency in HH compared to NH.[22,23] However, tidal volume and minute ventilation have been shown to be lower in HH compared to NH.[15,22] This suggests that HH might induce a higher alveolar physiological dead space at the same ambient Po_2.[15,22,23] These differences in physiological responses between NH and HH may lead to lower arterial saturation (S_ao_2) in HH compared to NH,[15,23] which may lead to greater cognitive and psychomotor performance impairments in HH compared to NH.

In everyday situations, pilots flying in unpressurized cabins are exposed to HH. The limited data currently available concerning the influence of NH, corresponding with oxygen pressures of 3048 to 5486 m (10,000 to 18,000 ft) suggest a decrease in flight performance. However, to the best of our knowledge, there is no published data examining the influence of HH on flight performance or physiological adaptation during flight. Therefore, the main purpose of this study was to examine the influence of HH on pilots' flight performance during exposure to three simulated altitudes: 91 (baseline), 3048, and 4572 m (300, 10,000 and 15,000 ft). We hypothesized that flight performance would decrease with increase in altitude, with the greatest decrease in flight performance at 4572 m compared to baseline. The secondary objective of this study was to measure the pilots' state of alertness and monitor their physiological adaptations during altitude exposures.

METHODS

Subjects

Volunteering to participate in this study were 12 male pilots (age = 31.6 ± 9.1 yr, weight = 79.1 ± 9.4 kg, height = 182.7 ± 6.3 cm, total flight hours = 1268.8 ± 1614.9). The group was evenly divided into six fix winged and six rotary pilots. All pilots had at least 50 h of flying a fixed winged aircraft and all were fixed wing instrument rated.

To be included in the study, the pilots needed to have passed their mandatory medical examination and been declared "fit to fly." Pilots were excluded if they were a smoker or reported staying for a period longer than a week at altitudes higher than 2438 m (8000 ft) 3 mo before the commencement of this study. Since no data were available from previous studies, the required sample size for the primary outcome measure was determined based on an a priori power analysis. The analysis showed that with an effect size of 0.25, 12 pilots were needed to achieve a power of 0.80 when testing at the two-tailed 0.05 alpha level. Each pilot provided written informed consent before participating. The study protocol was approved in advance by the Medical Ethical Committee of the Amsterdam Academic Medical Center.

Equipment

Altitude was simulated using the hypobaric chamber of the Centre for Man in Aviation at Soesterberg (the Netherlands). Measurement of flight performance was done using a Frasca 141 (Frasca international, Inc., Urbana, IL) single engine light aircraft flight simulator which was placed inside the hypobaric chamber. The Frasca 141 allows the pilot to perform flight maneuvers using instrument flying procedures. A Pilots Selection and Assessment System (PASS; Frasca international, Inc.) was used to run the simulator, present voice commands, and collect the flight data.

Monitoring the automated direction finder (ADF) adjustment was done using a GoPro HERO3$^+$ video camera (GoPro, San Mateo, CA). The camera was placed behind the pilot at the same height as the ADF panel.

An Oxycon Mobile breath-by-breath apparatus (CareFusion 234 GmbH, Hoechberg, Germany) was used to measure and record the following physiological parameters: heart rate (HR; bpm), oxygen saturation (S_po_2; %), minute ventilation (V_E; $L \cdot min^{-1}$), and breathing frequency (BF; rate/min). A Nonin 8000R forehead reflectance sensor (Nonin Medical, Inc., Plymouth, MN) was used to measure S_po_2 and a Polar T31 heart rate sensor (Polar Electro, Kempele, Finland) was used to measure HR. Both sensors were connected to the Oxycon Mobile. The physiological data collected were processed and displayed using JLab 5.72 software (CareFusion 234 GmbH).

Procedure

All pilots were exposed to three simulated altitudes of 91, 3048, and 4572 m (300, 10,000, and 15,000 ft) in a single-blinded counter-balanced within-subject design. Pilots' exposure order was randomly assigned using an online randomization software (www.randomizer.org). The simulated altitude was measured above ground level (altitude of the test facility is 18 m above sea level). The flight profile (**Fig. 1**) flown in this study was a flight profile formerly used by the Royal Netherlands Air Force for the selection process of pilots. The duration of the flight was 37 min. During the flight the pilots did not have any visual display and needed to rely on instruments only to perform the flight. The pilots received a flight mission data card, which they placed on their leg, containing information about the time and conditions [degrees of turn, direction of the turn, rate of turn (ROT), air speed during the turn, level-off altitude, new heading at the end of the turn, and air speed] in which they

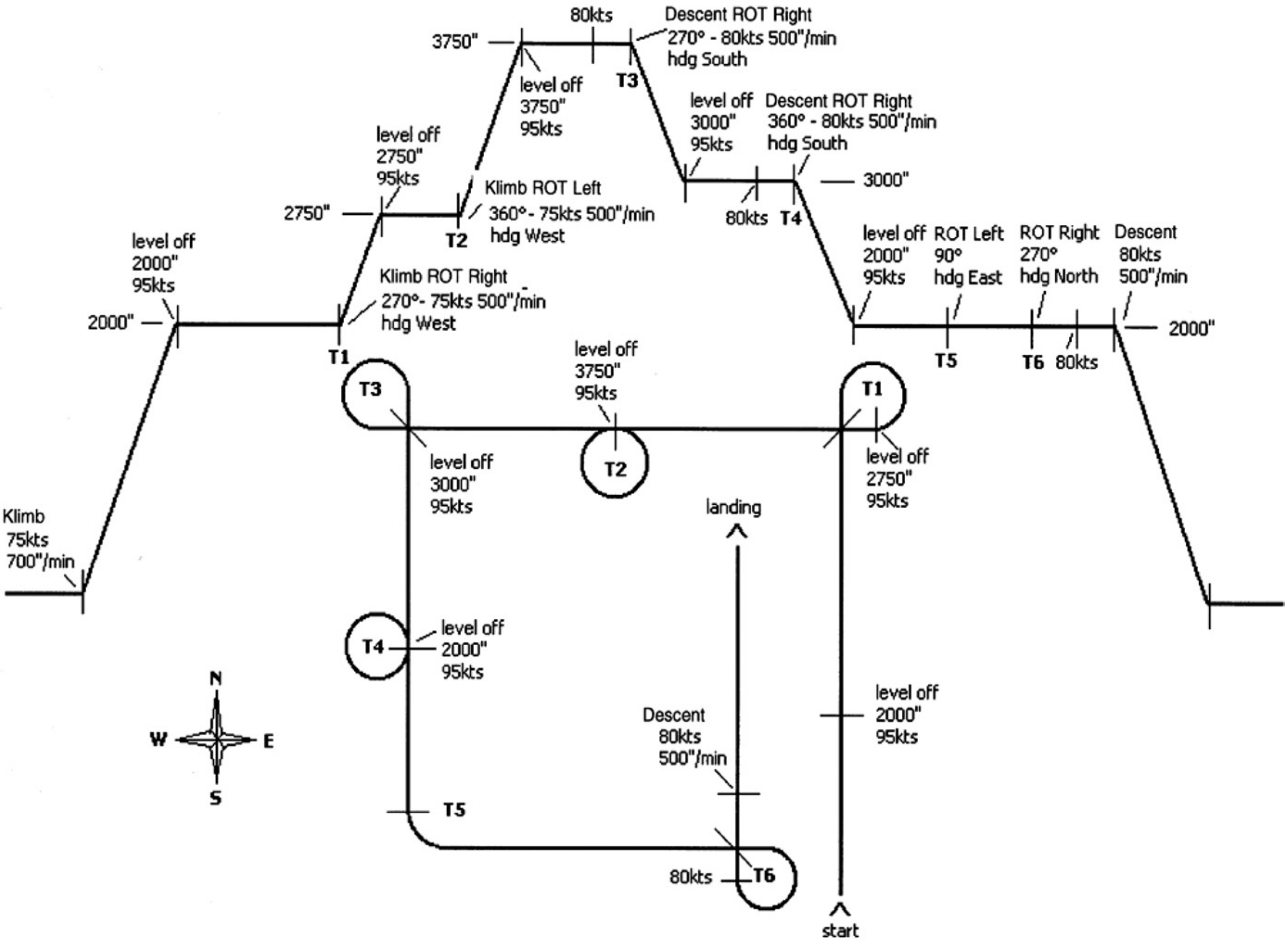

Fig. 1. A visual display (side and upper view) of the flight profile performed by the pilots containing the following flight information: degrees of turn, direction of the turn, rate of turn (ROT), air speed during the turn, level-off altitude, new heading at the end of the turn, and air speed. Source: Instructieboek Geautomatiseerd Vlieger Selectie Systeem, Koninklijke Luchtmacht, 2002 [Dutch] [Instruction book automated pilot selection system, Royal Air Force; 2002].

needed to execute each flight maneuver, and adjust the ADF (on the 1st, 2nd, 12th, 20th, and 24th minutes).

The flight profile was composed of takeoff, level flight, two 360° turns, three 270° turns, and landing. The first two turns were ascending turns, followed by two descending turns and a leveled turn. All the turns needed be completed in exactly 2 min. Two times during the flight, the pilots were instructed by the flight simulator to adjust squawk.

All pilots participating in the study received an instruction book 2 wk before the start of the familiarization sessions containing information regarding the flight simulator, the flight profile, power settings, and operation sequences during the flight. The pilots were asked to read the instruction book before coming to the first familiarization session. The pilots had three familiarization sessions spread over 3 d. On each of the familiarization days, the pilots practiced the flight profile two times. This was done to minimize any learning effects that might influence the study results. At the first familiarization session, the pilots received instructions regarding the hypobaric chamber, the flight simulator, the flight profile, and the questionnaire. They were instructed to fly the profile as accurately as they could. The sixth and last practice flight was performed with the pilot wearing all the measurement equipment that was used during the test day. This was done to ensure that wearing the measurement equipment did not interfere with the pilot's ability to operate the flight simulator and did not influence the pilot's flight performance score. All familiarization sessions were completed within 1 wk and took place at ambient level.

The experimental intervention was started within a week after completing the familiarization sessions to prevent any decline in their ability to execute the flight. Each pilot was exposed to the three simulated altitudes of 91, 3048, and 4572 m (300, 10,000, and 15,000 ft). The testing of each pilot was completed in a day. The pilots reported at the hypobaric chamber of the Centre for Man in Aviation around 08:00. After putting the Polar heart rate band on, the pilots entered the hypobaric chamber and ascending to altitude began. In each of the conditions, ascent to altitude took approximately 10 min. To mask the actual altitude in the 91-m (300-ft) condition, the chamber was first brought to a simulated altitude of 610 m (2000 ft) and then slowly lowered to 91 m. When the desired altitude was reached, a stopwatch was started and calibration of the Oxycon

Mobile was initiated to prevent errors in breath-by-breath measurements as a result of change in pressures at altitude. After completion of the calibration the pilots were fitted with the Oxycon Mobile and were seated in the flight simulator. Then measurements of the pilots' physiological parameters were started. The test flight started 20 min after the pilots were exposed to the simulated altitude to allow a new steady state of oxygen to be established in the body and cerebral circulation. The moment the pilot started the test flight and at the end of the test flight, markers were manually entered by the researcher onto the physiological measurements timeline.

Before the start of each flight and after completion of each flight, the pilots assessed their self-perceived state of alertness using the Stanford Sleepiness Scale[10] (SSS). The SSS is a 7-point Likert-type scale with descriptors ranging from "feeling active, vital, alert, or wide awake" (score = 1) to "no longer fighting sleep, sleep onset soon, and having dream-like thoughts" (score = 7). Afterwards, pressure in the hypobaric chamber was increased until it reached ambient levels. Descent to ambient level took approximately 10 min. The next test session started 1 h after reaching ambient pressure. During that hour, the pilots had time to rest, eat, and drink to reduce the chance of fatigue caused by exposure to the present altitude influencing pilots' performance when exposed to the next altitude. In addition, this may also help reduce the effect that performing a monotonous task might have on performance results.

The primary outcome measure was flight performance assessed by the Flight Profile Accuracy (FPA). During the flight, eight flight parameters were monitored. For each of the parameters, the pilots received penalty points for deviation from the flight profile (**Table I**). The FPA was calculated as the sum of all penalty points given for the flight parameters during the flight. Higher scores indicated worse flight performance.

Secondary flight performance measures were the ADF and squawk adjustments, the number of warnings, and the number of resets during the flight. If the pilot's deviation in one or more of the parameters was too big, a voice warning was given by the flight simulator, informing the pilot about the deviation. The warnings stopped the moment the pilot performed the right correction. If no correction was made by the pilot and the deviation from the flight profile became too great, the PASS would reset the parameter, correcting the deviation and returning the plane to the correct flight course. Receiving a voice warning or a reset did not add penalty points to the pilot's score.

Table I. Overview of the Eight Flight Parameters and the Penalty Points Per Flight Parameter Given By the System for Deviation from the Flight Profile.

FLIGHT PARAMETERS	DEVIATION PER SECOND	PENALTY POINTS
Altitude	2 ft	1
Indicated airspeed	1 kn	4
Heading	1°	6
Vertical Speed	10 fpm	1
Rate of turn	3°/s	1
Slip	10% ball off-center	4
Pitch	1°	15
Bank	1°	6

Penalty points were given for each second in which a deviation was measured in one or more of the flight parameters. The Flight Profile Accuracy was the sum of the total penalty points received in each of the eight flight parameters.

The ADF had to be adjusted correctly by the pilots five times during each flight. The squawk had to be adjusted twice during each flight. At the end of the flight the PASS system generated a flight summary report in which the penalty points, warnings, and resets were reported.

For the secondary objective of this study, the self-perceived state of alertness and physiological changes during exposure to HH were measured. Self-perceived state of alertness was measured using the SSS. A higher SSS score meant a lower alertness level. The physiological parameters were measured with a breath-by-breath analysis apparatus: HR (bpm), S_pO_2 (%), V_E ($L \cdot min^{-1}$), and BF (rate/min) were continuously measured during the flight during all three conditions.

Statistical Analysis

Using SPSS 18, all the data were checked for normality using frequency distributions, probability-probability plots (P-P plots), and the Shapiro-Wilk test. All nonparametric analyses are expressed as the median (Mdn) + interquartile range (IQR). All other data are expressed as the Mean ± SD. In this study the 91-m (300-ft) condition was considered to be the baseline measurement. In addition, all the post hoc analyses performed compared the results of the baseline and 3048-m (10,000-ft) conditions, and the baseline and 4572-m (15,000-ft) conditions.

A Friedman test was used to determine if a significant effect existed in the pilot's FPA between the three conditions ($P < 0.05$). If a significant difference was found, two Wilcoxon-Rank tests were run to determine the difference between the two altitude pairs ($P < 0.025$). A Cochran's Q test was applied to determine if a difference existed between altitudes in the following variables: number of resets during the flight, and ADF and squawk adjustments ($P < 0.05$). For the analysis, the data of these variables were converted into two outcome measures: "all correct" and "not all correct." Per variable, the score "all correct" was given when the pilots received no resets or made no mistakes in ADF or squawk adjustments during the flight. If a pilot's flight was reset, or ADF or squawk were incorrectly adjusted, a "not all correct" score was given to that variable. If a significant effect was found in one of the variables, two McNemar's tests were used to determine the difference between the two altitude pairs ($P < 0025$). Analysis of the number of warnings during the flight was done using repeated measures ANOVA. If a significant difference was found ($P < 0.05$), two paired-samples *t*-tests were used to determine the difference between the two altitude pairs ($P < 0.025$).

A Friedman test was used to determine if a significant effect existed in the pilot's state of alertness at the start of the flight between the three conditions ($P < 0.05$). If a significant difference was found, two Wilcoxon-Rank tests were run to determine the difference between the two altitude pairs ($P < 0.025$). Differences between the SSS score at the start of the flight and at the end of the flight within one simulated altitude were determined using a Wilcoxon-Rank test ($P < 0.05$).

The physiological parameters HR, S_pO_2, V_E, and BF were monitored during each flight. The physiological data produced by the JLab software was averaged over a seven-breath interval. For the analysis, average data from the beginning till the end of the flight at each altitude were used. Analysis of HR, S_pO_2, BF, and V_E was done using repeated measures ANOVA. If a significant difference was found ($P < 0.05$), two paired-samples *t*-tests were used to determine the difference between the two altitude pairs ($P < 0.025$).

RESULTS

FPA scores at each of the simulated altitudes are presented in **Fig. 2**. The results of the Friedman test showed a significant difference in FPA between the three conditions [χ^2 (2) = 6.5, P = 0.039]. Post hoc analysis showed no significant difference in FPA between baseline (Mdn = 111,454; IQR = 98,226–121,178) and 3048 m (10,000 ft; Mdn = 112,308; IQR = 97,232–126,501), and showed a trend [Z = −1.804, P = 0.077] between baseline and 4572 m (15,000 ft; Mdn = 120,356, IQR = 106,957–139,592). No significant difference was found between the conditions for the ADF and squawk adjustments or in the number of warnings and resets received during the flights.

Analysis of the SSS score at the start of the flight showed a significant difference between the three altitude conditions [χ^2 (2) = 10.118, P = 0.006]. Post hoc analysis showed that before the start of the flight, a significantly higher SSS score (Z = −2.507, P = 0.014) was given by the pilots at 4572 m (15,000 ft; Mdn = 2; IQR = 2–3.75) compared to 91 m (300 ft; Mdn = 1; IQR = 1–2). Alertness level of the pilots at the start of the flight at 4572 m (15,000 ft) was "functioning at high level, but not at peak" compared to "feeling active, vital, alert" at baseline. Comparison between SSS scores given at the start and end of each flight showed significant difference (Z = −2.754, P = 0.04) only at 4572 m (15,000 ft; Mdn = 2; IQR = 2–3.75 vs. Mdn = 4; IQR = 3–5; **Fig. 3**). Alertness of the pilots at 4572 m (15,000 ft) dropped from "functioning at high level, but not at peak" at the start of the flight to "somewhat foggy, let down" at the end.

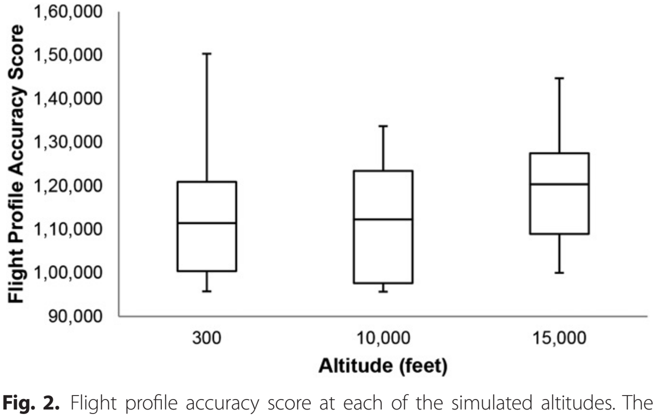

Fig. 2. Flight profile accuracy score at each of the simulated altitudes. The scores are presented as median, interquartile range, and range.

Repeated measures ANOVA revealed a significant effect of altitude exposure on HR [$F(2)$ = 13.774, $P < 0.001$], S_pO_2 [$F(1.236)$ = 194.226, $P < 0.0001$] (**Fig. 4**), and BF [$F(2)$ = 13.283, $P < 0.001$] (**Fig. 5**). No significant effect was found in V_E during exposure to altitude compared to baseline. Paired sample *t*-tests revealed that HR (bpm) was significantly higher [$t(11)$ = 5.567, $P < 0.001$] at 4572 m (15,000 ft; 95.5 ± 14.2) compared to 91 m (300 ft; 81.6 ± 10.5), whereas S_pO_2 (%) at 3048 m (10,000 ft; 89.3 ± 2.7) and 4572 m (15,000 ft; 71.5 ± 6.3) decreased significantly compared to baseline (98.6 ± 0.6) [$t(11)$ = 12.090, $P < 0.001$; $t(11)$ = 15.025, $P <$ 0.001, respectively]. In addition, BF (rate/min) was significantly lower [$t(11)$ = 4.267, $P < 0.001$] at 4572 m (15,000 ft; 14.3 ± 2.8) compared to 91 m (300 ft; 18.3 ± 2.9).

DISCUSSION

We sought to examine the influence of exposure to hypobaric hypoxia (HH) on pilots' flight performance. Initial analysis of the data indicated significantly higher FPA scores, meaning more errors during flight, between the three altitude conditions. Post hoc analysis, however, revealed no significant difference in FPA score between 91 and 3048 m (300 and 10,000 ft), and a trend was observed at 4572 m (15,000 ft) indicating a decrease in performance at this altitude compared to 91 m (300 ft). The observed trend of a decrease in flight performance was not unique to the present study. In their study, Gold and Kulak[8] observed similar trends of a decrease in flight performance in pilots exposed to an oxygen concentration equivalent of 3749 m (12,300 ft). Nesthus et al.[17] observed a trend in their study for more procedural errors in the hypoxia group compared to control during descent and approach at altitudes of 2438, 3048, and 3810 m (8000, 10,000, and 12,500 ft). Although it is difficult to make an adequate comparison between these studies and the present study due to different methodologies used and flight performance measurements, the results are similar: a trend toward decreased flight performance at altitudes between 3048 and 4572 m (10,000 and 15,000 ft). Both studies suggested that variability in the pilots' tolerance to hypoxia might be the reason for the inconclusive results.

Exposure to acute hypoxia has been shown to have a more profound effect on the cognitive performance of some individuals compared to others.[13,28] This is largely due to the result of differences in the individual respiratory response to hypoxia.[30] It has been observed that in individuals with a higher respiratory rate, cognitive performance was more impaired compared to individuals with lower respiratory rate,[11] presumably the result of hypocapnia-induced vasoconstriction and a subsequent decrease in cerebral blood flow.[1,19] Surprisingly, in contradiction with the expected elevated ventilation which accompanies hypoxia exposure, V_E did not change in the present study and BF decreased even though S_pO_2 decreased significantly. The cause of the deviant ventilatory response observed in this study is unclear. An autoregulatory response aimed at increasing brain oxygenation by mitigating the

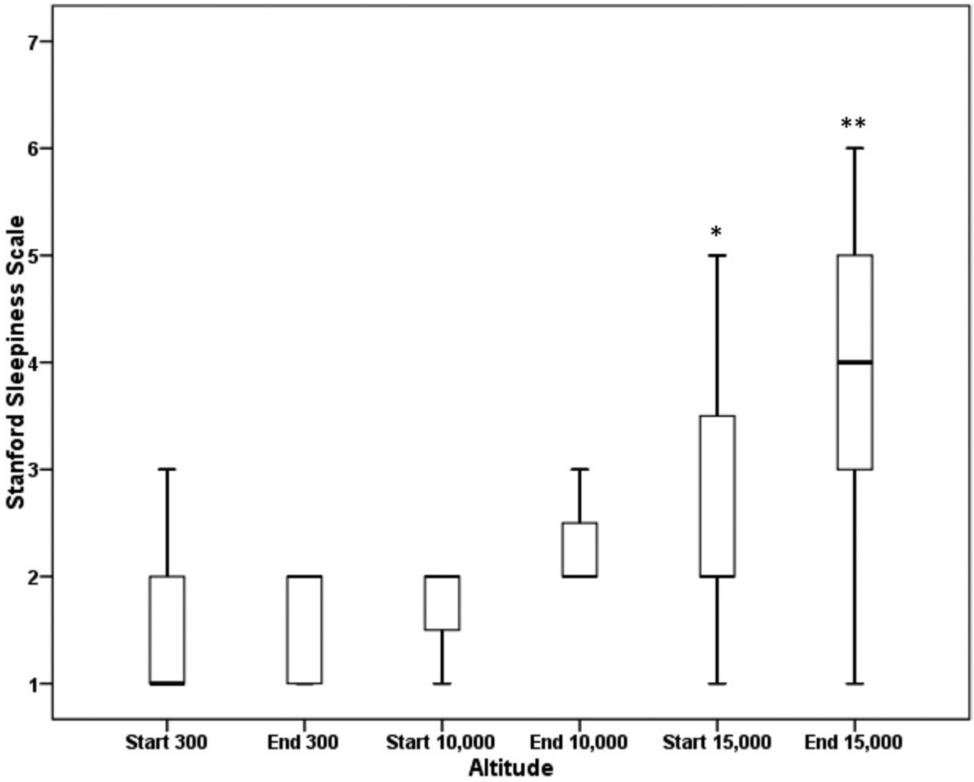

Fig. 3. Score of the Stanford Sleepiness Scale (higher scores are lower alertness) given by the pilots at the start and end of each of the flights at 91, 3048, and 4572 m (300, 10,000, and 15,000 ft). The scores are presented as median, interquartile range, and range. $*P < 0.025$ compared to 300 ft. $**P < 0.016$ compared to start of the flight.

decrease in cerebral blood flow caused by hypocapnia and increasing S_pO_2 levels in the body[4] might be one explanation. However, this is rather speculative and further research is needed to understand this autoregulatory mechanism.

In the present study, we decided post hoc to not only look at the group FPA average, but also to compare the individual FPA scores of the pilots between 91 and 4572 m (300 and 15,000 ft). Individual comparison of the FPA scores showed that, in 10 of the 12 pilots, flight performance, measured as FPA score, was worse at 4572 m (15,000 ft) compared to 91 m (300 ft). In 4 out of these 10 pilots, FPA scores worsened between 1 and 4%, 3 pilots showed a worsening between 6 and 9%, and 3 pilots showed a worsening between 12 and 16%. Thus, there was a large interindividual variation in the pilots' FPA score between the two conditions. These results put into question the ability of some of the pilots in the present study to safely fly an aircraft while exposed to an altitude of 4572 m (15,000 ft) without the use of supplemental oxygen. Further examination of the data revealed one outlier value in FPA score in the 91-m (300-ft) data that affected the results of the statistical analysis against finding an effect. The FPA score of this pilot was much worse at 91 m (300 ft) compared to 3048 and 4572 m (10,000 and 15,000 ft). This value was not excluded from the analysis since we could not find a valid reason as it did not deviate from the FPA scores during the training sessions of this individual.

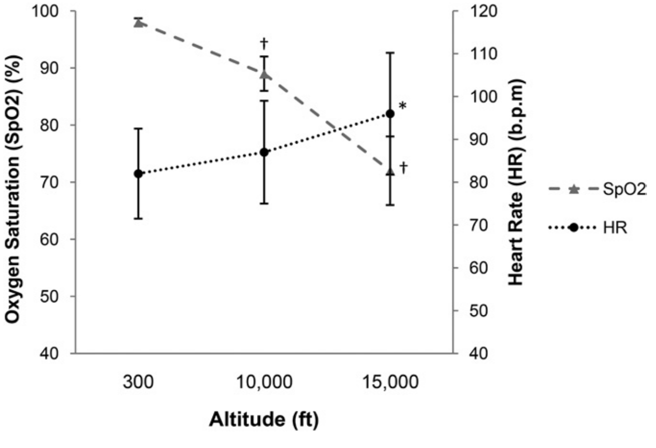

Fig. 4. Mean heart rate and oxygen saturation values during exposure to the three altitude conditions. Data are presented as mean ± SD. $*P < 0.025$ compared to baseline, $^{\dagger}P < 0.025$ compared to baseline.

We measured the alertness levels of the pilots at the beginning (after 20 min' exposure to the simulated altitude) and end (after 57 min' exposure to altitude) of the flight using the Stanford Sleepiness Scale. The decrease in pilots' alertness level at the start of the flight at 4572 m (15,000 ft) can be contributed to the hypoxia exposure, as reduced alertness or being sleepy is one of the most common hypoxia symptoms reported by aircrew.[12,25,28]

The pilots in the present study reported lower alertness levels at the end of the flight at 4572 m (15,000 ft) compared to the start of the flight. During flight, lower alertness levels have been shown to influence cognitive performance[29] and impair performance of tasks requiring attention, vigilance, and accuracy in pilots.[31] As flight performance is influenced by alertness levels, gradual decrease in alertness levels as a result of prolonged exposure to hypoxia may further decrease the pilots' ability to fly an aircraft. In addition, prolonging the hypoxic exposure durations may lead to a decrease in flight performance at altitudes which are considered "safe" to fly, as reported in the study of Vaernes et al.,[28] which examined the effect of 6.5 h of exposure to 3048 m (10,000 ft) on cognitive performance of individuals. They found that prolonged hypoxic exposure resulted in graduated decrease in cognitive performance of some cognitive tasks (reasoning, long-term memory, visual digit span, visual reaction time). In addition, they found large

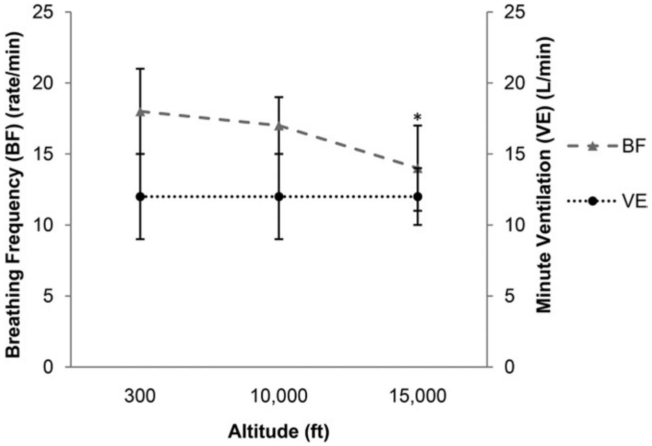

Fig. 5. Mean minute ventilation and breathing frequency values during exposure to the three altitude conditions. Data are presented as mean ± SD. *$P < 0.025$ compared to baseline.

interindividual differences in cognitive performance and impairment levels. During operational flights, the continued drop in pilots' alertness levels, as a result of prolonged hypoxia exposure during flight, becomes a hazard as it would further reduce pilots' efficiency and impair pilots' performance.

Several limitations exist in the present study which need to be acknowledged. During flight, depending on the deviation of a flight parameter from the flight profile, the PASS system generated voice warnings or performed a reset of that flight parameter. By doing that, the system made the pilots aware of an error or corrected an error they made (without adding penalty points to their FPA score), which otherwise might not have been noticed or corrected by them. This potentially resulted in the pilots receiving less penalty points than they normally would have. It is difficult to evaluate the effect of receiving the warnings and resets might have had on the results of this study. However, we think the effect was negligible as analysis showed no significant differences between the number of warnings and resets received at each altitude. Through the lack of comparison studies, power calculation was based on assumptions of the hypoxic effect on FPA. Increasing the number of pilot participants, regardless of the sample size calculation, could have resulted in a clearer effect of hypoxia on flight performance. However, because of the amount of time the pilots needed to invest in the present study, pilot recruitment was difficult. Since trying to recruit an additional 6 pilots would have extended the duration of the research far beyond its planned time, it was decided to end the measurements when 12 pilots were reached. The overall flight profile required the pilots to perform multiple flight-related operations simultaneously. However, the test flights performed at altitude were identical to the flights during the training sessions. A study by Andre et al.[2] showed that when pilots had a preview of increasing workload demands during flight, they tended to perform task scheduling in order to reduce workload. This scheduling has been observed during the present study as the pilots who were aware of what was going to happen next adjusted their flight behavior in accordance. It is possible that in the present study this reduction in workload limited the effect of hypoxia on cognitive performance, which has been shown to be impaired at these altitudes.[3,28] Future studies of flight performance under hypoxic conditions may require using variable flight profiles and tasks to limit the effect of scheduling on the results. In addition, flight-related stressors like noise, vibration, and thermal stress, which were not present during the present study but are present during normal flight, may further decrease the individual's tolerance to hypoxia, leading to a greater reduction in flight performance.[18]

In conclusion, the present study did not provide decisive evidence for a decrease in flight performance during exposure to simulated altitudes of 3048 and 4572 m (10,000 and 15,000 ft). The present study did, however, reveal a large interindividual difference in flight performance which may be the result of variability in individual tolerance to hypoxia. We also observed a gradual decrease in alertness levels with increased altitude caused by prolonging the hypoxic exposure. The literature suggests that variability in the pilots' tolerance to hypoxia combined with the exposure duration to the hypoxic conditions may influence pilots' flight performance not only at extreme altitudes, but also at altitudes which are considered "safe." It is important to acknowledge these individual differences in hypoxia tolerance. Since during flight the cockpit is normally manned by only one or two pilots, incapacitation of a pilot as a result of low hypoxia tolerance may put flight safety in danger. Therefore, we recommend the use of supplementary oxygen during flights in unpressurized aircrafts, especially with aircrew involved in complex tasks, to prevent the adverse effect of hypoxia on alertness levels, and thus on flight performance.

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