Original Article

Hypoxia indoctrination in the altitude simulator - A new approach

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Indoctrination of aircrew on the effects of acute hypoxia in a man rated decompression chamber is standard practice is most Air Forces the world over. In the IAF the practice involves ascent to 30,000 ft. simulated altitude and demonstration of manifest psychomotor performance decrement in the form of a deterioration of a given handwriting task. This practice has numerous pitfalls and suffers from lack of objectivity, is unrealistic and has a poor test job correlation. A new computerised flight oriented performance task (FOPT) has been developed at IAM for indoctrination of aircrew. The test measures performance changes by a scoring system of seven flight parameters of a subject while being exposed to simulated hypoxia. The scores obtained at altitude are compared with the mean and SD scores obtained at ground level. The test has been administered to 11 subjects at 30,000 ft. altitude. The degree of deterioration using this task has been ascertained and compared with the handwriting task deterioration. The results are discussed.

Keywords: Flight performance task, psychomotor performance, aircrew training.

Altitude induced hypoxia is an ever present potential threat in flying and constant awareness and vigilance on the part of the pilot is essential for the safety of man and mission. To offset hypoxia in aviation, aircraft are pressurised and/or provided with a pilots personal oxygen system. Consequently failure of aircraft pressurization and/or of personal oxygen breathing equipment will expose any aviator to sudden and life threatening hypoxia. This is the commonest mode of developing hypoxia in modern aviation. In addition hypoxia may be encountered in some types of commercial cargo flying where aircraft may not be pressurised or in flying for sport if pilots inadvertently fly higher than the stipulated safe limit of hypoxia in aviation i.e. an altitude of 10,000 ft. Rayman and McNaughton [1] in a study conducted to identify causes of hypoxia in the USAF between 1970-80 found that out of the 298 cases reported, 27% were due to operator error, 20% were due to decompression of the pressure cabin, 16% were due to regulator malfunction, 4% were due to miscellaneous causes and 33% of the causes were unknown. They concluded that 27% of the cases of hypoxia could have been avoided by proper oxygen discipline. They also found that the maximum episodes of hypoxia occurred at an altitude between 16-20,000 ft. (26%) followed by 21-25,000 ft. (17%). In another study conducted over an eight year period in a military airforce [2], in which 400 cases of hypoxia were reported, it was noted, that nearly half the incidents involved student pilots operating unpressurised jet trainer aircraft. Over a third of incidents were due to malfunction of oxygen equipment and a further third was due to failure to use it correctly. In the IAF there is incomplete documentation of cases of hypoxia in military aviation, However at least 1

Department of HAP Institute of Aerospace Medicine IAF

cases of hypoxia due to equipment malfunction are on record [3].

It is therefore, imperative firstly to make pilots aware of the overt effects of hypoxia and secondly, to train them to recognize and prevent hypoxia. Defining and demonstrating the performance degradation produced by acute hypoxia of altitude has, therefore, important connotations towards flight safety. Indoctrination of aircrew in a decompression chamber is the established practice the world over. The testing involves exposure to simulated high altitude and demonstration of psychomotor performance decrement in a rather crude and unrealistic way by administering a simple handwriting task. Other methods of assessing performance decrement are using conventional psychological tests unrelated to flying in any way. The results obtained from conventional psychomotor tests are difficult to extrapolate because of poor test-job correlation and have been proved to be contradictory on occasion [8].

The detrimental effects of overt hypoxia have been known for a long time but effects of mild hypoxia on higher mental functions and performance are difficult to quantify, however, they are no less important to flight safety and assume a special significance in the Indian high altitude flying environment. Numerous studies are available to qualify and quantify the effects of different degrees of hypoxia on human performance [2,5-15]. The results so obtained have been used to broadly define decrements in psychomotor and cognitive performance in terms of specific and standard psychological tests. Extrapolation of such tests to the complex but well learned task of flying an aircraft has its inherent disadvantages. Specific flying related questions like subtle but significant performance decrement, types of flying tasks affected at a particular altitude, time to decrement and upper limit of safe hypoxia exposure especially at medium altitudes have still not been answered with certainty. One of the reasons for this has been the widely varying nature of tests used for assessing performance decrement under hypoxia. The tests used range from cognitive tasks, various forms of psychomotor testing apparatus and psychological tests [2,7-15] to flying actual aircraft [5] and ground based trainers [6]. These tests have generally measured both psychomotor and cognitive performance decrements in a hypoxic environment but how they translate in actual flying of the aircraft remains uncertain. Surprisingly, none of these tests are used for hypoxia indoctrination of aircrew.

The advent of microprocessor technology has drastically changed the face of experimental research. The operational imitation of the real process in the laboratory has become a reality and the presence of such an environment offers unprecedented opportunity [16]. Simulators, originally developed with the objective of training of aircrew, are being increasingly used for performance assessment [17]. Today, it has become possible to model complex mathematical equations and generate high quality graphical images on the personal computer (PC).

This study was designed with an intent to use this technology for developing a PC based Flight Oriented Performance Task (FOPT) for performance assessment with relevance to the flying environment. The task so developed was used for assessing hypoxia induced performance decrement under simulated hypoxia in a decompression chamber or altitude simulator (DC) during high altitude simulation.

Material and methods

This study was carried out in three stages. Firstly, FOPT was developed with the help of a commercial software company. In the second stage a computer was installed next to the control station of the DC and was linked to a dedicated computer video terminal inside the chamber through a specially designed wire looming using a special aircraft quality connector such that the vacuum characteristics of the DC were not affected. In the third stage the FOPT developed was tested on volunteers for evaluating its use for indoctrinating aircrew in the effects of hypoxia.

Chamber modifications for the FOPT. For the purpose of carrying out this study, a few additions/modifications were carried out on the chamber. A new phalange was manufactured for the communication port in the chamber external shell and a 37 pin vacuum-sealed aircraft quality connector was fitted on it to prevent any leakage during the decompressed state of the chamber. A special cabling of approximately 7 meters was carried through the pin connector to connect a video display terminal (VDT), the joystick and the throttle from inside the chamber to a PC kept outside the chamber. This was essential, as commercially available computers do not function optimally in low pressure or near vacuum situations existing in decompression chambers. The entire looming and pin connector system was designed and developed by engineers from the Aeronautical Development Establishment (ADE). Care was taken to ensure that there was minimal signal loss and no change in the signal characteristics across the length of the cable. It was achieved by installing a specially developed line driver in the PC.

Test equipment: The equipment used to administer the test was an IBM compatible PC fitted with a 32 bit 80486-DX 2 microprocessor. The central processing unit (CPU) was placed outside the simulator. This was connected to two VDTs in parallel, one of which was kept outside and the other inside the simulator. The input devices consisted of a 101 keyboard and a serial mouse connected to the main PC located outside the simulator. Inside the chamber a specially designed joystick and throttle were placed on a fixed platform base, ergonomically placed and designed, to stimulate an aircraft cockpit in position and dimension. The CPU placed outside the chamber was driving the joystick and the throttle. All this equipment was interconnected through a 37 pin connector and the special cabling arrangement described above. The structural and the functional integrity of the equipment and the connections were successfully tested up to an altitude of 30,000 ft. with an exposure for a period of over two hours.

The Test: New software, the FOPT, was specifically conceptualized and designed. The FOPT was designed to be an interactive computerised flight stimulator to be run within the specific constraints and limitations of the available hardware. The mainstay of the FOPT was an on screen display of the inside of a cockpit showing the primary flying instruments in the lower half of the screen and a special graphical output to simulate ground features was shown on the upper half of the screen. The display was seen simultaneously on the main computer screen as well as the VDT inside. The image displayed on the VDT consisted of the view as seen from within the cockpit of the aircraft. The lower 30% of the screen displayed the instrument panel and the upper 70% the outside view including the horizon. A network of lines forming a grid pattern that receded and converged into the horizon marked the "ground". This grid pattern was made to move in a manner as to stimulate visual motion cues for the subject as also to provide a feeling of depth in the field.

The instrument panel displayed, from left to right: the throttle setting indicator with 50%, 75% and 100% power settings, the air speed indicator (ASI): the maximum speed attainable at full throttle setting and level flight at 1 km altitude was 750 km/h., the altimeter: a long pointer indicated altitude in hundreds of meters whereas the shorter pointer indicated altitude in km. The "aircraft crashed" if it continued in a pitch down attitude (descending mode) beyond the altitude of 0 km. The attitude indicator was an "inside-out" type. The outer rim was marked at 30°, 60°, and 90° to indicate the bank angle of the aircraft when in a turn. The artificial horizon in addition also moved down/up in case of pitch up/down attitude of the aircraft.

The magnetic compass, had a fixed dial and movable pointer, was graduated every 5° and had digital markings every 30°. The four cardinal points were depicted. It also had an automatic direction finder (ADF), depicted as a blue pointer, indicating the absolute heading of the airfield from the aircraft. The vertical speed indicator (VSI) which during level flight showed the needle as pointed to the zero position indicating a zero rate of ascent/descent. The turn and bank indicator: it indicated the rate of turn of the aircraft in degrees per second. In addition there was a red horizontal warning display bar above the altimeter, which randomly appeared and was to be switched off by a definite pilot/subject action to measure reaction time. A digital distance from the airfield indicator along with a digital timer in the right hand bottom corner of the screen was also available. Metric units were used in the markings of the display.

The flight movements were co-ordinated using a joystick and a throttle so fixed in position and distance as to simulate an actual cockpit environment. Special care was taken throughout to make the final product as realistic as possible, visually and aerodynamically. The joystick was used as input for the commands of pitch up, pitch down, left bank, right bank or a combination of these, to the CPU. The forward displacement of the joystick translated to pitch down, the backward displacement to pitch up, left lateral displacement to left bank and turn and the right lateral displacement to the right banking and turning of the aircraft.

A number of mathematical equations of aerodynamics were incorporated into the software design for computation of the various parameters and the responses of the simulated aircraft and were based on the flight characteristics of the IAF trainer aircraft, Kiran Mk I.

The thrust of the aircraft was a direct function of the engine rpm and the two were linearly related. The angle of attack was kept constant at 0.5 degrees.

Defining the Mission/Task: Any specific flying task incorporating the parameters of altitude, pitch, rate of climb, heading, bank, rate of turn and speed can be given to the subjects.

Scoring and Results: On completion of the task by the subject, his performance could be viewed immediately. The flight profile of the aircraft during the performance of the task is seen in the form of a graphical display of the seven flight parameters plotted against the time axis. These were altitude, rate of turn, rate of climb, bank angle, heading, pitch of the aircraft and speed. In addition simple reaction time was also assessed. The total time taken to complete the task was also known. The subject's performance is analysed, parameter by parameter, by noting the scores obtained for each parameter. These scores are calculated on the basis of deviation of the subject's performance from the ideal performance. An ideal performance line is generated by the computer based on the known parameters of the defined task and is plotted by the computer along with the subject's performance profile as another line. The area between the two lines is then calculated and presented as a figure, which is the score. The score obtained in each parameter thus was directly proportional to the degree of deviation from the ideal and the duration of the deviation from the ideal. The greater the area between the two (ideal and actual performance) lines, the greater are the scores obtained and greater the deviation from the ideal indicating performance decrement. As the subjects practise flying the simulator at ground level, coloured lines, depicting their performance, are plotted for each run against the ideal curve which is depicted as a different colour line. The computer computes the mean and standard deviation of all the base line runs. This is the baseline mean score with standard deviation. Runs at altitude are recorded in different coloured lines. The computer then determines the score between the altitude run(s) and the mean baseline score and this is the performance decrement. The task to be performed could mean climbing to a particular altitude, maintaining a particular rate of climb and simultaneously executing a turn at a specified bank angle to a specified new heading. Since ideal, baseline and altitude runs for each parameter, are in different colours they can be visually compared and shown to the subject who is better able to appreciate his performance at ground level and at altitude, under the influence of hypoxia. Based upon the performance of the individual, the in-built evaluating software of the FOPT automatically analysed and generated an overall total score and an average score per unit time for each of the parameters mentioned above. The values thus obtained were used for calculation and statistical analysis.

The experiment: The FOPT was next evaluated with reference to its utility for indoctrinating aircrew in the effects of hypoxia in the DC as compared to the current practice of using a simple non specific handwriting deterioration task for the same. 11 healthy, adult males (6 aircrew and 5 non-aircrew) were selected as subjects. The number of subjects were small but in such experiments larger number of subjects are not possible due to the hazardous nature of such experimentation. All the subjects were explained the experimental protocol in detail.

Each of the subjects was seated in the DC at the console where the VDT, joystick and throttle were mounted. All the eleven subjects got a minimum of 50 practice runs each, and in certain cases even more practice sessions for individuals were given in case it was felt that the learning curve of the individual had not flattened out. Finally, each subject was given the test at the ground level 10 times to obtain the mean and SD ground level or base line scores for each individual.

The actual test involved 'flying' the simulator for a given task at ground level followed by at the simulated altitude of 30,000 ft which is the established practice being followed in the IAF. All subjects performed the same allotted task so as to achieve standardisation of the results. Once in the chamber the individuals were subjected to 30 minutes of pre-breathing with 100% oxygen to achieve denitrogenation of the body tissue. This was done to minimise the risk of decompression sickness. Before ascent to the target altitude, the subjects were given an ear clearance run to 8,000 feet at the rate of 3,000 ft per min and back to ground level at the same rate. Thereafter, each of the subjects were taken to the simulated altitude of 30,000 ft @ 3000 ft/min and made to undergo the selected task immediately on exposure to altitude and repeatedly thereafter till performance deterioration was evident to the observer monitoring the test on the outside VDT. At this point handwriting of the same subject was also sampled to determine if there was concomitant handwriting deterioration.

The task selected involved "climbing from an altitude of 1 km to 1.7 km at the rate of 20 m/s and at the same time turning from a heading of 150 degrees to a heading of 330 degrees at a bank angle of 60 degrees". All through the task the individuals were required to maintain a constant aircraft speed of 600 km/h and also switch off the red warning light as soon as they detected it.

Results

The FOPT was used to assess the performance decrement in 11 healthy male volunteers (6 aircrew and 5 non-aircrew) under simulated hypobaric hypoxia. The age range of the subjects was 23-31 years (mean 25.91 ± 2.17 years).

Out of a total 165 observations (11 subjects x 15 parameters) made during the course of this study, there was a deterioration in performance on 142 occasions and an improvement on 23 occasions under the influence of simulated hypobaric hypoxia of 30,000 ft (Table 1).

Exposure to hypoxia produced an improvement in the parameter of heading (total and average) on

Table 1. Summary of deterioration/improvement seen in various parameters under hypoxia

Sub ject	Alt		Spd		Hdg		Pit		Bnk		Roc		Rot		
	Tot	Avg	Tot	Avg	Tot	Avg	Tot	Avg	Tot	Avg	Tot	Avg	Tot	Avg	Tot time
A	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
B	IMP	IMP	***	***	IMP	IMP	***	***	***	***	***	***	***	***	***
C	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
D	***	***	***	***	***	***	***	***	***	***	***	***	***	***	IMP
E	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
F	***	***	***	***	***	***	***	IMP	***	***	***	IMP	***	***	***
G	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
H	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
I	IMP	IMP	IMP	IMP	IMP	IMP	***	***	IMP	IMP	***	***	IMP	IMP	IMP
J	***	***	***	***	IMP	IMP	***	***	***	***	***	***	IMP	IMP	IMP
K	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***

Legend: Alt: Altitude, Spd: Speed, Hdg: Heading, Pit: Pitch, Bnk: Bank, Roc: Rate of Climb, Rot: Rate of turn, Tot: Total score, Avg: Average score, IMP: Improvement, "***": Deterioration.

6 occasions, altitude (total and average) and rate of turn (total and average) on 4 each, total time taken on 3, speed (total and average) and bank (total and average) on 2 each and on one occasion each for pitch (average) and rate of climb (average). The improvement in parameters were mainly noticed in subjects 'B' and 'I'. These 2 subjects may not have reached the peak of their learning curve. This was more obvious for subject 'I'.

Subjective symptoms: All the subjects (100%) reported a very conscious need to actively concentrate on the performance of the task when subjected to the simulated hypobaric hypoxia. 6 of the 11 subjects (54.5%) also reported a brief failure of concentration at some point or the other while performing the task. This lapse was however soon realized and the individual resumed the task. 3 out of 11 subjects (27.3%) reported tingling of fingers and lips towards the end of the exposure to hypobaric hypoxia. 1 out of 11 subjects (9.9%) developed intense headache on termination of the chamber run. This however improved after sometime on return to the ground level.

Comparison with standard indoctrination practice of handwriting task: In none of the subjects did a simple handwriting task given at the end of the FOPT show any deterioration. Thereby indicating that while performance of a flying task deteriorated the current practice of performing a handwriting task was not sensitive enough or demonstrative enough to be accepted as a useful and meaningful method of hypoxia indoctrination of aircrew.

Discussion

Indoctrination in the effects of hypoxia is an established norm in the training of aircrew in all air forces the world over. Training is imparted in the adverse patho-physiological effects of hypoxia, but even more important is the manifestation of hypoxia wherein a pilot's performance in the air can be affected without his or her knowledge and this can lead to catastrophic disaster of the worst kind. Training schedules the world over include actual exposure to simulated low pressure conditions in a DC to altitudes of 25,000 ft or 30,000 ft with or without oxygen and the aircrew are made to experience their own responses. They are also asked to perform simple cognitive tasks like performing arithmetic sums or any mentally absorbing task which they find difficult to do or are shown colour slides wherein their colour perception under hypoxia is altered [18]. Such tasks are hardly indicative of the flying environment, which involves very complex cognitive and psychomotor skills, which are usually well learned. Such crude methods of demonstrating performance decrement in a simulated environment therefore may not show the desired results. This leads to erroneous conceptions in the minds of the aviator and defeats the very purpose of the training. Also at very high altitudes these relatively crude performance changes are more easily manifest but at medium and lower altitudes such a change take very long to appear or may not appear at all. This is why altitude indoctrination is done at very high simulated altitudes (> 25,000 ft). In the IAF, hypoxia indoctrination is carried out at the ab initio stage in pilot trainees which is essentially done at No. 2 Aeromedical Training Centre for all flight cadets and subsequently in trained pilots also though the latter is not mandatory. In the US Air Force high altitude training is essential ever 3 years for all aircrew [18]. Personal experience by the first author, of training over 500 flight cadets in the DC has shown that using the present technique for performance assessment and demonstration viz. administering a handwriting task at an altitude of 30,000 ft does not cause manifest changes in almost 50% of the aircrew exposed. Therefore this study is an attempt to evolve a test for performance evaluation which simulates and has relevance to the actual flying environment and can not only be used for training of aircrew but also as performance tool for measurement of performance under any simulated stress.

The FOPT has been developed as a computer based flight simulator. The software has been so engineered as to perform as an aircraft with actual characteristics and mathematics of flight without a moving based platform. Such an approach in performance evaluation of various other stresses has been used [19,20,21] but not in the measurement of hypoxia stress, though a similar concept has been used by Gold and Kulak [6]. This may be so because performance of simple personal computers, in a low pressure environment like in a DC, can be seriously affected. In our study, the experimental set up was quite unique in that a computer placed outside the chamber controlled a monitor, throttle and joystick all placed inside the chamber on a special table such that all controls and the display unit were at almost the same levels and distances one would encounter in an aircraft. Certain video games/ commercially available game oriented flight simulators can also be used [17]. However such simulators cannot be used in this scenario because they do not have a standardised scoring pattern which is easily reproducible and 'visible' to aircrew. The scoring pattern in this simulator was to compare an ideal computer generated curve of the specified task performance with a ground run generated curve and finally a curve generated by performance of the specified task at altitude. Area under the curve between the ground run and the altitude run was available as a numerical score. The need for an ideal curve for comparison was considered essential because the ground or altitude curves may be higher or lower than the ideal and in either situation would signify performance decrement.

The task selected was one which aircrew would normally perform in the course of a training sortie in an actual aircraft. It involved cognitive and psychomotor performance in terms of short term memory, attention, judgement, vigilance, tracking, spatial orientation, complex eye-hand co-ordination, muscle co-ordination and conceptual reasoning and at the same time simple reaction time was being continuously assessed by the switching off the red light as and when it appeared.

The task had seven components namely pitch, heading, bank, speed, rate of turn and rate of climb and total time taken to complete the task in addition to reaction time. In each of these parameters the total score divided by time was taken as the average score. The results obtained for each showed that some parameters showed decrement and were statistically significant in their outcome whilst other parameters were in the expected direction but were not statistically significant. The 'p' values of the various parameters are summarized in the Table 2 below.

Table 2. 'p' values of various parameters of FOPT at 30000 feet altitude

$p<0.005$	$p<0.01$	$p<0.05$	$0.05<p<0.1$	$p>0.1$
ROC(tot)	ROC(avg)	ALT(tot)	HDG(avg)	HDG(tot)
PIT(tot)	PIT(avg)	ALT(avg)	Total time	
SPD(tot)		BNK(avg)	BNK(tot)	
SPD(avg)			ROT(tot)	
			ROT(avg)	

ROC: Rate of Climb, PIT: Pitch, ALT: Altitude, ROC: Rate of Climb, SPD: Speed, BNK: Bank, HDG: Heading, TOT: Total, AVG: Average

A significant change was noticed in the parameters of Speed (total and average), Altitude (total and average), Pitch (total and average), Rate of Climb (total and average) and Bank (average). These aspects of the task demanded total attention, fine judgement, good eye hand co-ordination, attention to complex detail and conceptual reasoning. These higher functions were significantly affected during the simulated altitude exposure thereby indicating adequate sensitivity to pick up such performance changes early.

However the parameters of Heading (Total and average), Bank (Total), Total time taken to complete the task and Rate of Turn (Total and average) were not significantly affected. This is contrary to what was expected because at 30000 feet the time to performance decrement is known to be around 75 seconds and all aspects of performance are expected to be severely affected at such high altitudes. Normally the rate of turn to achieve a certain degree of bank angle to achieve a new heading would involve good attention span, short term memory, eye hand co-ordination, vigilance and judgement, faculties which are known to be affected at much lower than 30000 feet simulated altitudes [2]. These parameters are evidently interrelated and because of the relatively insensitive joystick not much interaction was required on behalf of the pilot to execute these maneuvers, once he banked the simulator to the desired level, by lateral deflection of the stick no further interaction was required. This aspect has been taken care of in a later version of the FOPT where the joystick requires a constant interplay with the pilot. However, the results produced by these parameters are variations in the expected direction.

This study has one again substantiated the fact that performance produced by hypoxia is a function of task complexity used to assess the same. As has been seen above, the degree of decrement produced for the parameters of Heading, Bank and Rate of Turn, where the subject interaction with FOPT was minimal, is much less than for the parameters of Altitude, Pitch, Rate of Climb and Speed where the subject had to constantly take corrective actions. This relationship between task complexity and performance degradation under hypoxia has been brought out by other authors also [2,7].

A few of the subjects actually showed an improvement in some of the parameters under the influence of hypoxia. This was probably because in their endeavour to perform well, these subjects over concentrated on these parameters. This was however at the cost of other parameters, which got neglected and ultimately the overall performance of the individual suffered. However one subject (subject I) showed an improvement under hypoxia in 11 parameters out of a total of 15 monitored. This individual was not an aircrew and it is possible that his learning curve had still not peaked when the tests were administered to him. He therefore improved with every practice/test run and performed better in the hypoxia runs that were administered after he had completed the ground level runs.

The general outcome of this phase of the study has been in the expected direction in that it has shown the decremental effects of hypoxia on human performance. It has shown performance changes, which can critically but subtly endanger man and mission and it has shown it in a manner that was lucid and impressive onto the aviator. It has shown changes when the simple handwriting task, being currently administered for hypoxia indoctrination, did not show any deterioration. In all the 11 subjects the performance decrement was only known to the subject on completion of the run. To this end the results of this study did achieve a basic platform on which further modifications have been made in the hardware and software.

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