

Simulation In Aviation: Hypoxia Familiarisation Training Using The GO2Altitude® System.

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Abstract

Background: Since the earliest days of aviation, simulation has been used in both flight and safety training. Altitude hypoxia has been recognised as a serious safety hazard and the Australian Transport Safety Bureau (ATSB) website lists 15 recent incidents between 1999-2004 involving hypoxia and loss of cabin pressure. It is known that hypoxia training of flight personnel aids early recognition of individual symptoms, but until now, there has been no cost-effective and easily accessible device for such aircrew safety training in Australia. This paper presents the results of validation trials of an integrated hypoxia training system for the aviation industry. **Aims:** To compare objective and subjective effects of hypoxia familiarisation training at simulated altitude using two different gasmix methods. Such training to increase awareness of insidious hypoxia at altitude should reduce hypoxia-related incidents and accidents. **Methods:** GO2Altitude® hypoxia training system produces hypoxic air that is delivered by mask, with continuous recording and display of physiological parameters and cognitive functions. **Results** using the GO2Altitude® system in 80 subjects show blood oxygen level, heart rate and breathing, impairments of cognitive performance, motor and visual sensory functions and thought block similar to those presented previously. A comprehensive report is automatically printed for each individual, stored on video CD and database. **Conclusions:** We conclude that simulation of 25,000ft altitude using GO2Altitude® system now provides safe, efficient practical hypoxia training and familiarisation for flight personnel. They experience their own individual time of useful consciousness and hypoxic symptoms, without risks of barotrauma or decompression sickness. This training complies with CAO20:11 and CAR 253 and should facilitate hypoxia awareness.

1. Introduction

1.1. Simulation of Flight Environment: Although a number of electro-mechanical devices to simulate aspects of flight were tried prior to and during World War 1, the first effective flight simulator was developed by Edward Link in 1927-1929 [1]. This had a replica fully instrumented cockpit mounted on a motion platform, providing pitch, roll and yaw. Closing its canopy lid simulated flying through cloud and was able to teach instrument flying in a safer less expensive environment than in the aircraft. There was little interest in this until 1934, when a series of fatal accidents in instrument flight stimulated the US Airforce to purchase six Link trainers. Many tens of thousands of aircrew in USA, UK, and even in Japan and Germany, were trained using these simulators before and during World War 2. After WW2, enormous and rapid expansion of commercial aviation and the increased safety and cost effectiveness of such simulator training spawned many generations of new simulators. Indeed, aviation simulation is a whole industry and is still evolving.

1.2. Hypoxia at Altitude: Engle & Lott [2] described the first fatalities from aviation hypoxia occurring in April 1875, when two young Frenchmen, Croce-Spinelli and Sivel, during their attempt to reach 26,200 feet in an open balloon. Harding [3] states that acute hypobaric hypoxia is the most serious single hazard during flight at altitude, and it remains a serious threat today. Hypoxia is a condition of decreased oxygen availability which triggers various cardiovascular

and respiratory adjustments in the body. Despite such compensations, hypoxia causes impaired visual functions, cognition, motor control, and ultimately severe incapacitation and death.

Island & Frayley [4] provide the USA National Transportation Safety Bureau statistics (NTSB) documenting 40 aircraft accidents related to hypoxia between 1965 and 1990, resulting in 67 fatalities. During that time, the USAF lost 1 aircraft and had 1 fatality due to hypoxia. Many fatal accidents occurring as a result of hypoxia may not be immediately recognised as such, given the many other potential causes. However, Wolff [5] cites a few hypoxia accidents which have occurred dramatically to remind all aviators of this ever-present altitude threat. In October 1999, a Lear Jet 35 crashed near Aberdeen, South Dakota killing all on board including professional golfer Payne Stewart. Cabin pressurisation failure and hypoxia are the probable causes of this accident. In 2005 the crash of a Helios Airlines B737 in Greece again raised the probability of undetected hypoxia leading to crew incapacitation, reminding aviators about the importance of altitude physiology knowledge. Wolff stresses that early recognition of hypoxia is critical in preventing incapacitation to enable corrective actions to be taken. Sudden explosive decompression is self-evident but hypoxic symptoms from slow or unrecognised depressurisation are often subtle and may be difficult to recognise without previous training. Depending upon the altitude, there is often very limited time for aircrew to recognise any hypoxia symptoms before losing consciousness.

Impaired cognitive ability due to hypoxia may negate the efficacy of automated warning systems. Previous incidents involving Australian Civil aircraft have demonstrated the gravity of the threat. Theoretical training is required by CAO20:11 and CAR 253, but by adding practical training for flight crew the early detection of cabin decompression and hypoxia is facilitated.

This paper presents results from a new training technique using GO2Altitude® system which can provide an accessible means of hypoxia training for Australian civilian flight crews where no facility has been previously available. GO2Altitude® hypoxia training system uses a nitrogen concentrator to produce a gas with the desired low oxygen concentration, unlike other normobaric methods [6] which utilise bulky gas cylinders and have high maintenance and running costs. Smart & Cable [7] describe the RAAF hypoxia training using a Combined Altitude Depleted Oxygen (CADO) technique to blend a safer chamber altitude of 10,000 ft and depleted oxygen gasmix, to avoid barotrauma and decompression illness. The US Navy Reduced Oxygen breathing Device (ROBD) of Sausen et al [8] uses oxygen and nitrogen from cylinders to provide normobaric hypoxic experience in a dedicated aircraft simulator. Both are costly, relatively inaccessible for civil aviators and neither provides detailed automated printout of physiological data, continuous cognitive test results and video-recorded behaviour.

2. Aims of Study:

Using our GO2Altitude® Hypoxia Training System we wished to demonstrate and provide evidence about the reliability, utility and efficacy of this hypoxia familiarisation training system for the aviation sector (civil or military). This has been done by comparing objective and subjective effects of hypoxia training at simulated altitude using two different gasmix methods. Measuring physiological changes and cognitive effects of hypoxia induced with GO2Altitude®, documenting hypoxia symptoms experienced by students and pilots enabled comparison of the GO2Altitude® system with previous reduced oxygen breathing methods, specifically Westerman [6]. We also consider issues of training fidelity in using a hand-held mask for hypoxia training. By attaching the pulse oximeter to a finger of the hand holding the hypoxicator mask, we distinguish it from the quick-don masks fixed in place by aircrew as part of emergency procedures. The ultimate aim which cannot be measured in this study, is to improve aviation safety by providing practical hypoxia familiarisation for aircrew, cabin crew and others.

3. Methods:

We compare two methods of normobaric hypoxia familiarisation training which simulated altitude of 25,000 ft (7620 m) to demonstrate and measure

(1) cardiorespiratory adjustments in healthy volunteers; (2) the spectrum of signs and symptoms accompanying such hypoxia; (3) individual variability in susceptibility to hypoxia and oxygen paradox; (4) time of useful consciousness. Trainees encounter the insidious onset, individual symptoms and obvious performance decrements resulting from hypoxia.

3.1 A Normobaric Reduced Oxygen Breathing Method (ROBM) This is described in detail by Westerman [6] who used commercial gasmix of 6.5%–7% oxygen, balance nitrogen, held in 100 L flexible milk-bags with a 2-way tap and hose connected to a SCUBA mouthpiece with one-way valves expiring to air via a Wright respirometer. Subjects wore a nose clip, with continuous Propaq monitoring of blood oxygen saturation (SpO₂) pulse rate, blood pressure, and ventilation. A written cognitive function test battery lasting approximately 90 seconds was administered repeatedly until obvious impairments were observed. Symptoms experienced by each individual were ticked from a list by subjects after they had recovered from the hypoxia produced during their simulated altitude exposure. The data reported in this paper were gathered from 1990 – 2002 from medical under- and post- graduate students and MICA air ambulance trainees.

3.2. GO2Altitude® Hypoxia Training System: is a normobaric reduced oxygen breathing technique for hypoxia training, which is a cost-effective and efficient system [9]. The GO2Altitude® hypoxia training device utilises a nitrogen concentrator to produce air with the desired low oxygen concentration and permits continuous computer monitoring of cognitive and physiological functions during hypoxic exposures simulating up to 40,000ft. Subjects were 95 healthy male and female non-smoking subjects, aged 18 to 50 years, 80 of whom were naïve to hypoxia training or hypobaric exposure. The research plan was to compare data recorded using the GO2Altitude® Hypoxia Training System with previous data obtained from the ROBM [6], seeking statistically significant differences. The effects of a simulated altitude of 25,000ft achieved using these methods are compared in this paper.

3.3. Safety Screening: All subjects held current Australian Class 1 medical certificates and had undergone a screening medical examination by a Designated Aviation Medical Examiner consistent with civil aviation medical practice. This included history, physical examination, near and distant visual acuity, colour vision, audiogram and resting electrocardiogram. Subjects would be excluded from the study if they suffered from any aeromedically significant illnesses, abnormalities on physical examination, special tests, or any adverse medical history.

3.4 Education and Briefing: All subjects received a standard briefing on the effects of simulated altitude, nature of hypoxia, and all measurements and monitoring to be taken. The majority were naïve to any previous hypoxia or high altitude exposure. They were briefed on the potential hazards of simulated altitude exposure and hypoxia and conditions which would exclude them undertaking the actual hypoxia exposure. In GO2Altitude® hypoxia familiarisation system the computerised educational package provided most of this briefing.

3.5 Consent and Ethics: Subjects all gave written informed consent after receiving verbal and written information on the study design, risks, and voluntary nature of their participation. The research protocol was approved by The Alfred Human Research Ethics Committee (proj. 40/07).

3.6 Induction of hypoxia: This was achieved by the two methods which are compared in this paper. Namely, by reducing inspired oxygen concentration to approximate 7% (balance nitrogen) under normobaric conditions using either a commercial gas mixture (British Oxygen Corporation) or GO2Altitude® hypoxicator. Each exposure to simulated 25,000ft was limited to 5 minutes, with rapid recovery effected by breathing oxygen. A subject seated at a GO2Altitude® hypoxia training system is illustrated in Fig.1.

3.7 Physiological Testing: Subjects were supervised at all times by a physician or MICA attendant, ACLS accredited. Subjects had baseline measures in a normoxic normobaric environment, SpO₂ by pulse oximetry, heart rate, respiratory frequency, heart rate variability were non-invasive physiological parameters recorded and displayed on the touch screen – see Fig 1.

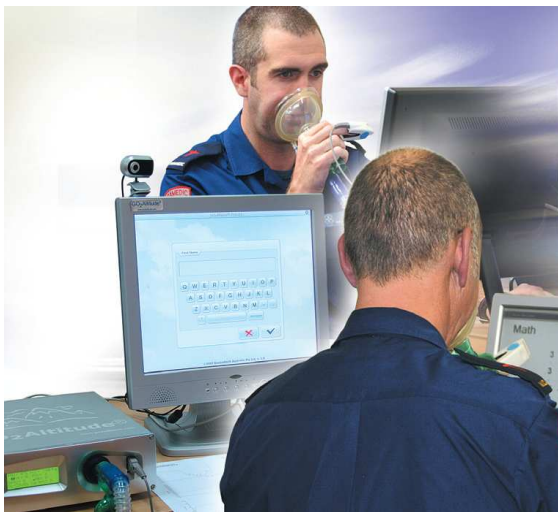


Fig1. GO2Altitude® Hypoxicator System - Touch screen, mask, pulse oximeter and video-recording of behaviour can be seen

3.8 Cognitive Function Testing: This was assessed continuously during each hypoxia exposure. The previous ROBM used pencil and paper tests described and illustrated in Westerman [6]. In the GO2Altitude® hypoxicator system a short computer-presented cognitive test battery was developed and refined from standard subtests similar to those employed in the aviation modules of neuropsychological test batteries. Parameters assessed included simple and choice reaction times, simple maths processing, spatial orientation, memory, shape discrimination and colour vision (BK, Ishihara or similar plates). Subjects were allowed sufficient time before the hypoxia testing to fully familiarise themselves with the test sequence, protocol and cognitive function subtests.

3.9 Symptom Survey: After each hypoxia experience subjects were asked to complete a survey containing a list of hypoxia-specific, non-hypoxia-specific and non-hypoxia symptoms. Key hypoxia symptoms have been analysed and compared between the two hypoxia exposures.

3.10 Data Analysis and Reporting: All data was de-identified and analysis was undertaken from Excel files with Chi squared analysis of the symptom and cognitive data and two-tailed t-tests for the non-matched samples physiological measures using a significance level of $p < 0.05$ where appropriate.

Set out below is Figure 2 Cognitive Function tests and Figure 3 - Physiological measures, which are both displayed on the touch screen of the GO2Altitude® Hypoxia Familiarisation system.

4. Results:

4.1 Using a Reduced Oxygen Breathing Method: physiological adjustments previously observed in 452 subjects included tachycardia, cyanosis and hyperventilation. Many subjects showed neuromuscular incoordination, tremor, twitching, illegible writing and poor reproduction of geometric figures. Simple arithmetical calculations, immediate and delayed recall with serial 7 subtractions, and delayed recall of a fictitious name and address were frequently impaired, usually when SpO₂ was between 50% and 60%. Perseveration of thought (expressed in writing) was a common finding. Visual symptoms, dysaesthesia and headache were often described. Detailed results are set out in the paper by Westerman [6].

4.2 Using the GO2Altitude® hypoxia training system, the results from 80 naïve subjects show similar changes in oxygen saturation (SpO₂), heart rate (HR) and breathing frequency (Vf) displayed on the screen and user station, together with an increase in simple and choice reaction time, and an impairment of math processing, short term memory, spatial orientation, shape discrimination and colour perceptual acuity.

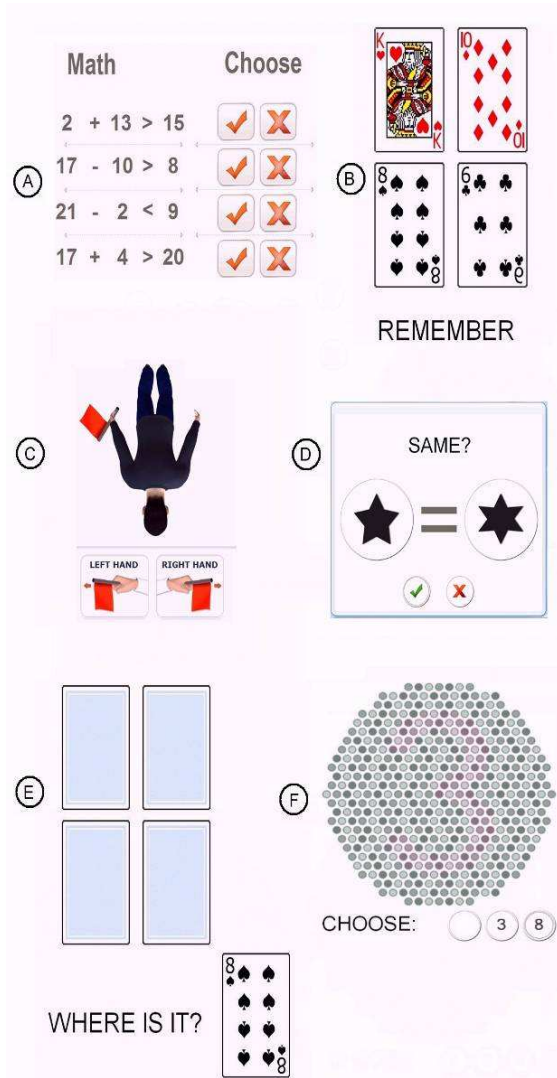


Fig. 2 Touch screen display of Cognitive tests



Figure 3. Continuous Physiological measures

Results of the continuously monitored changes in these physiological parameters, including heart rate variability, are presented to each subject on an individual comprehensive report printed, stored on video CD and database. The results are summarised in Table 1. Physiological changes induced by both ROBM and GO2Altitude® simulated altitude training system included falling SpO₂, increased heart rate, depth and frequency of ventilation, and cyanosis. Estimated time of useful consciousness (TUC) was not significantly different for the two methods, nor were the physiological responses of increased heart rate and increased respiratory frequency. For the 80 subjects using the GO2Altitude® system, mean SpO₂ at the end of TUC was slightly higher (58% vs 52%), but not significantly different from the larger ROBM group.

TABLE 1: Physiological Cardiorespiratory Adjustments to Reduced Oxygen Breathing During the Time of Useful Consciousness (TUC) at pO₂ equivalent to 25,000 ft.

ROBM 1995-2004 Subjects N=452 (M274/F178)	TUC (min)	Mean HR (bpm) Start/End ΔHR =33	Nailbed O2 Sat (n=138) Start/End 96% / 52%	Resp. frequency (b/min) (n = 249) Start/End 11.2 / 14.6 Δf = 3.4
	3.20 ± 0.65			
GO2Altitude® SATS Subjects N=80 (M70/F10)	TUC (min)	Mean HR (bpm) Start/End ΔHR =29	Nailbed O2 Sat (n=80) Start/End 96% / 58%	Resp. frequency (b/min) (n = 80) Start/End 11.5 / 16.4 Δf = 4.9
	2.92 ±0.81			

The usual cognitive effects of hypoxia at the simulated 25,000ft altitude were performance degradation, reduced accuracy, lengthened response time to subtest completion for maths, spatial orientation and shape discrimination, impaired memory and colour perception, deteriorated handwriting, and perseveration even

“freezing” or failure to respond. These cognitive effects of hypoxia are shown in table 2 comparing effects of hypoxia using the two methods. All subjects who completed the hypoxic exposure were cyanosed and the range of SpO₂ was 48%–74% when the observed impairments of cognitive function led to termination of the hypoxia. No

differences between groups were significant except and 88% GO2Altitude®. A possible explanation is impaired computational functions with 46% ROBM given in discussion.

Table 2: Observed Cognitive Effects of reduced oxygen breathing (hypoxia equivalent to 25.000 ft) in 452 subjects using ROBM 1995-2004 or 80 subject using GO2Altitude® 2007

	n=452 ROBM 1995-2004		n=80 GO2Altitude® SATS, 2007	
Impaired Memory Functions	401	89%	59	69%
Immediate recall (serial 7's & cards)	288	64%	46	53%
Delayed recall	213	47%	10	13%
Graphic memory (clock or writing)	84	19%	19	22%
Impaired Computational Functions	207	46%	76	88%
Maths Completion Time increased			76	88%
Simple Arithmetic Errors	207	46%	65	76%
Impaired CNS Decisions or Execution	175	39%	38	44%
Repetition in writing or calculations	175	39%	28	33%
Impaired Visual Motor Functions	113	25%	33	38%
Motor Incoordination (illegible writing, drawing)	98	22%	30	35%
Poor geometric figure reproduction	81	18%	33	38%
Block in writing or calculations	73	16%	18	21%
Neuromuscular Disturbances	96	21%	35	41%
Tremor or muscle twitching	96	21%	35	41%
Colour Visual Disturbance- ↑errors			25	29%
Colour Detection-Finish time ↑			59	69%
Cyanosis	452	100%	86	100%
SpO₂ at Time of Useful Consciousness		42-61%		48-74%

5. Discussion:

Impaired computation differences between the older ROBM group 46% and GO2Altitude® 88% are most likely to be due to the more difficult calculations and time limited presentation in the GO2Altitude® maths problems. Paradoxically, despite the known risks of hypoxia and the documented aviation incidents listed above, practical hypoxia training for civilian aircrew is not mandated by legislation. It almost appears there is a prevailing perception in civil aviation that hypoxia incidents are rare, and if they do occur, emergency oxygen, warning systems and rapid descent will save the situation and prevent hypoxia. In a recent survey of 67 professional pilots in the USA by Hackworth et al, [10] almost all indicated that they believed that altitude chamber training should be conducted both ab initio and recurrently, especially for commercial and airline transport flight crews. Most believed that the need for training should be based on the

altitude capabilities of the types flown. In the past, the major factors inhibiting the ability to conduct hypoxia training for civilian aircrew has been the poor availability of hypobaric chambers, their capital cost, maintenance expense, and the risk of decompression illness. Given a perception of minimal risk of hypoxia in the civil aviation industry, it is therefore not surprising that training is dismissed as impractical on the basis of cost-benefit analysis. However, if an accessible, inexpensive and effective alternative was available, the financial equation may look much more favourable.

Over the last 10-15 years, physiologists and aerospace medicine researchers have developed and trialled ground-based methods of training which use reduced oxygen gas mixtures to simulate the physiology of high altitude. Sausen et al [8] developed one such device which uses a closed loop breathing circuit with computer controlled fraction of inspired oxygen. This device

has been proven effective in inducing hypoxia in subjects under normobaric conditions. Hypoxia induced by normobaric ROBD was concluded to be equivalent physiologically and symptomatically to that induced by hypobaria. Non-rebreathing normobaric systems have also been studied and found effective in demonstrating hypoxia effects to students and Air Ambulance personnel at Monash University [6],

As a result of the threat that hypoxia poses to military aviators, and based on the kind of data presented above, air forces around the world have conducted hypoxia familiarisation training for aircrew for at least the last 70 years, traditionally using hypobaric altitude chambers. The training is recurrent to refresh their awareness of symptoms and identify any changes in an individual's symptoms. It is widely acknowledged that, while symptoms are idiosyncratic to the individual, they are consistent over time for that person. There is now good evidence that such training works and saves lives. In Island & Fraley's report [4], 656 USAF hypoxia incidents described above, 606 of the cases involved trained aircrew, and only 3.8% of these experienced loss of consciousness as a result. Of the 50 passengers, 94% experienced loss of consciousness. The study concludes that this major difference between trained aircrew and untrained passengers emphasises the benefit of hypobaric chamber training in the recognition of hypoxia. Of the 520 trained aircrew who

recognised their own symptoms, 26.2% stated that they were "just like the chamber". Similar results were found in the ADF study in which 86% of hypoxia-trained aircrew recognised symptoms in themselves or in others and took corrective actions.

6. Conclusions:

Reduced oxygen breathing by the GO2Altitude® hypoxia training system to simulate 25,000 ft altitude sessions is a safe, convenient and effective way to train and familiarise aviators, and paramedical personnel with the objective physiological and cognitive effects of hypoxia. They experience their own individual "time of useful consciousness" and subjective hypoxic symptoms, without risks of barotrauma or decompression sickness. This should increase recognition and awareness of hypoxia at altitude, and so prevent or reduce hypoxia related incidents and accidents. There may be policy implications or recommendations stemming from this study. Australian aviation legislation currently does not make provision for routine practical hypoxia training of flight crews and other flight personnel: only theoretical safety training is mandated by CAO20:11 and CAR 253. In the future, with an easily accessible, safe, inexpensive, user-friendly and effective training method now available, legislative changes to training requirements may be contemplated.

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