SCIENTIFIC COMMENTARY

USE OF OXYGEN FOR RECOVERY IN HYPOXIA AWARENESS TRAINING: WHAT IS OPTIMAL?

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ABSTRACT

These technical notes summarise current practices of oxygen recovery after exposure to hypoxia as part of awareness training. Most air forces use traditional hypobaric chambers in their recurrent hypoxia awareness training of aircrew in which recovery after hypoxia is achieved with 100% O_2. Now, normobaric hypoxia technologies are commonly being used to replace or supplement hypobaric chamber training. Gas mixtures simulating 25,000ft, or hypoxicators such as ROBD-1, ROBD-2, and GO2Altitude are used for hypoxia demonstration, with either pure oxygen or 'hyperoxic air' being used for recovery. A recent case report of oxygen paradox is described[1] where worsening of symptoms, loss of consciousness and seizure occurred when pure oxygen was delivered as recovery from hypoxia. This case stimulated speculation about optimal gas composition for recovery after severe hypoxia. Physiological equivalence of hypoxia produced by normobaric hypoxicators, hypobaric chambers, and combined altitude / depleted oxygen conditions (CADO) is assumed, but significant differences exist and have been measured[2]. From our experience, all trainees achieved full arterial oxygen saturation (SpO_2), heart rate (HR) and cognitive performance recovery after exposure for 3-7 minutes to physiologically-simulated altitude of 25,000 ft using slightly hyperoxic air (F_iO_2 0.33) rather than 100% oxygen. These observations suggest the need for additional experimental data and controlled studies examining different methods of recovery from hypoxia in both hypobaric and normobaric environments.

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INTRODUCTION

Whilst working on the specification for the Australian-developed normobaric hypoxia awareness training system, the authors were required to detail the oxygen concentration in the gas provided for the trainee recovery at the end of practical hypoxia demonstrations. The 'gold-standard' practice with traditional hypobaric chambers is to use pure oxygen to recover from the hypoxia experience at 25,000ft. For the sake of meaningful comparison between recovery actions following hypoxia taking place in a *hypobaric* environment and hypoxia taking place in a *normobaric* environment, it is important to consider the alveolar equivalence of the recovery actions, and it is important to calculate what partial pressure of oxygen must be delivered in a normobaric environment to be equivalent to the 100% oxygen delivered at 25,000ft. It is also important to consider what other factors may be affecting the accuracy of normobaric hypoxia simulation[3,4].

HYPOXIA AWARENESS TRAINING TECHNOLOGIES

Since late 1930s, the traditional hypobaric chamber has been the de-facto standard for military aviation hypoxia training around the world[5]. The aims of hypobaric chamber training are to demonstrate the effects of rapid decompression and allow trainees to experience their individual hypoxia symptoms. Demonstration of impairment of various cognitive functions commonly uses pen-and-paper cognitive tests[5], hardly changed since the 1950s.

Over the last two decades, normobaric hypoxia 'mask-on' training devices have been introduced as alternatives to the traditional hypobaric chamber[6,7,8,9.]. Although these normobaric systems differ from hypobaric chambers in the way they produce hypoxia, all forms of hypoxia training have the same aim: to induce hypoxia in subjects and demonstrate defective cognitive performance on some tasks.

For the purpose of describing new classes of devices for inducing normobaric hypoxic hypoxia in trainee-pilots, Sausen et al[6] suggested an acronym ROBD (Reduced Oxygen Breathing Device). The early ROBDs were based on a 're-breather' system similar to an anaesthetic apparatus[6]. The second-generation of ROBD devices was developed through collaboration with US Navy Aeromedical Research Laboratory and Environics, a company that specialises in mixing and blending industrial gases[7]. This device used a gas-mixer to combine compressed air, N_2, and O_2 to produce an oxygen-depleted gas mix to produce hypoxia. The intended use of this device – the 'ROBD-2' – is that an operator programs the gas mixer to deliver hypoxic air at a physiological equivalent to the target simulated altitude. During the simulation, the operator must visually monitor the subject's physiological response (SpO_2 and HR), impairment of cognitive function, at the same time as eliciting and discussing the subject's individual hypoxia symptoms. To make training sessions relevant to the aviator, trainees engage in a simulated flying task (in a part-task trainer or desk-top flight simulator), and perform relevant corrective actions to initiate recovery when they detect hypoxia[7]. Training sessions are ended at the discretion of the ROBD-2 operator, at which time trainees breathe pure oxygen through their well-fitted military oxygen mask[7].

The normobaric hypoxia awareness training system GO2Altitude® developed in 2004 by Biomedtech Australia was initially intended as a classroom-based multi-person task-nonspecific hypoxia education system[8,9]. Later, the design of the system was extended to allow for its use with a military oxygen mask and inspiratory demand regulator. Because the function of the GO2Altitude® device is to make subjects hypoxic reversibly, free from adverse-effects, BIOMEDTECH used the term "hypoxicator" to describe their device. The design of the GO2Altitude® hypoxicator not only delivers hypoxic gas that is physiologically equivalent to the pre-programmed altitude, but it also produces the required hypoxic and hyperoxic gasmix onsite using semipermeable membrane air-separation technology, and also monitors, displays, and records physiological parameters (SpO_2, HR, and ventilatory frequency). The training session automatically aborts if a safety threshold is reached. During the hypoxia awareness demonstration, trainees can concentrate on performing cognitive tasks and experiencing their individual symptoms without frequent interruptions from an instructor. For the objective demonstration of individual cognitive function deterioration and the insidious nature of gradually developing hypoxia, a battery of computerised cognitive tests is delivered to the trainee

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in a repeating loop[8,9]. It was demonstrated that neurocognitive testing by computer[10], rather than paper-and-pencil tests, enhances demonstration of the subject's susceptibility to hypoxia and helps measure individual variability objectively[10]. The session terminates automatically when: the student exceeds one of the pre-determined thresholds for SpO_2 and HR, the instructor decides that the trainee has reached their Time of Useful Consciousness (TUC), or if the trainee wishes to terminate it by pressing the ABORT button[7,8]. Once the hypoxia demonstration has finished, oxygen-enriched air (FiO_2 up to 40%) is automatically supplied via the same breathing circuit[8,9].

Both commercially available systems described above have proven track records in their ability to deliver hypoxic air for hypoxia demonstration, but the ROBD-2 uses 100% oxygen to recover from hypoxia[7] whereas GO2Altitude® hypoxicators recover the student with an oxygen-enriched gas-mix containing FiO_2 not greater than 40%[8,9].

CALCULATION

It is possible to estimate the tracheal oxygen tension when breathing 100% oxygen during the recovery phase following a hypoxia experience using the following formula[12]:

(Formula 1) $PTO_2 = (P_B – PH_2O) \times FiO_2$

Where:

PTO2 is the tracheal oxygen tension;

P_B is the barometric pressure;

PH_2O is the partial pressure of water vapour in the trachea, taken to be 47 mmHg; and

FiO_2 is the fractional content of oxygen in the inspired gas.

When breathing 100% oxygen at a hypobaric altitude of 25,000 ft (ambient pressure 282 mmHg), the partial pressure of oxygen in the trachea is:

(Formula 2) $PTO_2 = (282 – 47) \times 1.0 = (235) \times 1.0 = 235$ mmHg

When breathing 100% oxygen to recover following a normobaric hypoxia experience at sea level (ambient pressure 760 mmHg), the partial pressure of oxygen in the trachea is:

(Formula 3) $PTO_2 = (760 – 47) \times 1.0 = (713) \times 1.0 = 713$ mmHg

It is also possible to calculate the FiO_2 at sea level required to reproduce the tracheal oxygen tension of Formula 2:

(Formula 4) $PTO_2 = (760 – 47) \times 0.33 = (713) \times 1.0 = 235$ mmHg

Using this simple formula, it is clear to see that breathing 100% oxygen at sea level produces a tracheal oxygen tension significantly greater than would be produced by breathing 100% oxygen at a hypobaric altitude of 25,000 ft. However, breathing an oxygen-enriched gas-mix of FiO_2 of 0.33 at sea level produces the same tracheal oxygen tension.

Normobaric hypoxicators are designed to produce a hypoxia experience that is physiologically equivalent to hypobaric hypoxia. These calculations use the same foundational formula that underpins the physiological equivalence of the hypoxia demonstration to produce a recovery action that is also physiologically equivalent to that in a hypobaric environment. GO2Altitude has applied the principle of physiological equivalence to the post-hypoxia recovery phase, and the GO2Altitude uses an oxygen-enriched gas-mix of FiO_2 not greater than 40% during the recovery phase following normobaric hypoxia.

From the calculation above, and our clinical experience, we believe that recovery action using normal room air, or air that is only slightly enriched with oxygen, after severe hypoxia exposure at near sea level, approximates what happens when persons breathe pure oxygen at altitude or in a hypobaric chamber.

There are other factors that are known to affect the accuracy of normobaric hypoxia altitude simulation, including variations in atmosphere and temperature conditions, as well as instrument error[3,4]. The possibility of error introduced by expired water vapours was suggested by Conkin[11]. However, we have previously reported that PH_2O in *expired* air is unrelated to the accuracy of PO_2 in air *inspired* by the trainee[3,4], and that no compensation for this factor is needed[12]. Such correction in fact would introduce a new error and inconsistency with existing training practices because no correction for alveolar PH_2O is made when a hypobaric chamber technician configures the chamber altimeter settings, and pilots do not correct their stated altitude by the amount of water vapour in their lungs.

The incidence of oxygen paradox in chambers at 25,000 ft using pure O_2 for recovery may be different to that using normobaric techniques because the effect of breathing 100% oxygen at sea level is not the same as breathing pure oxygen at 25,000ft.

CONCLUSION

We believe that use of pure oxygen as the recovery gas following normobaric hypoxia demonstrations is not physiologically equivalent to recovering on 100% oxygen following a hypobaric hypoxia experience. The use of 100% oxygen at sea level produces a tracheal oxygen tension significantly higher than that produced in a hypobaric environment, and it may not be optimal as the recovery gas. To generate an accurate physiological reproduction of the traditional hypoxia demonstration in a hypobaric chamber as well as the oxygen recovery following the demonstration, the partial pressure of oxygen for recovery at sea level has to be adjusted as well. Our calculations indicate the most appropriate FiO_2 to reproduce the physiology during recovery is FiO_2 0.33.

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