

Mask-On Hypoxia Training for Tactical Jet Aviators: Evaluation of an Alternate Instructional Paradigm

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Introduction: Hypoxia familiarization instruction has been an integral part of military aviation training for more than 60 yr. Traditionally, aircrew learn hypoxia recognition while being exposed to hypobaric conditions in a low-pressure chamber (LPC). A training device has been developed that induces hypoxia using mixed gas delivered through an aviator's oxygen mask. The reduced oxygen breathing device (ROBD) simulates the diminished oxygen present at altitude by mixing breathing air and nitrogen under normobaric conditions. The purpose of this paper is to describe an alternate hypoxia training paradigm that combines the ROBD with tactical flight simulators and to present results from student surveys. **Methods:** Dynamic hypoxia instruction was provided inside F/A-18 tactical flight simulators using a second generation ROBD (ROBD-2). There were 121 naval aviators who were individually exposed to a simulated altitude of 7620 m (25,000 ft) while performing complex flight duties. Subsequent to ROBD training, all students completed a 19-question, anonymous survey that asked them to rate the quality of the instruction. **Results:** Of the 121 students trained with the ROBD-2 in combination with a flight simulator, 114 (94.2%) were able to recognize their hypoxia symptoms and recover the aircraft, 117 (96.7%) rated ROBD training as more realistic, and 110 (90.9%) as more effective than traditional LPC training. **Discussion:** Student feedback from this instructional evaluation indicates that using an ROBD in combination with actual flight duties is a safe, effective, and preferred means of training experienced tactical jet aviators to recognize and recover from hypoxia.

Keywords: aerospace physiology, altitude chamber, low-pressure chamber, reduced oxygen breathing device.

HYPOXIA HAS LONG been cited as one of the most frequently encountered hazards in aviation medicine (7,10). In Ernsting and King's classic book on the subject, Harding stated that hypoxia is generally recognized as "the most serious single hazard during flight at altitude" (4). In the early days of aviation, scientists described catastrophes resulting from hypoxia during balloon and aircraft flights, while deterioration of physical and mental capabilities caused by hypoxia was often cited as a significant physiological problem during World War II (7). Even today, hypoxia remains a potential threat to aviators who routinely fly above 3048 m (10,000 ft). Although fatalities from hypoxia are normally considered rare events, the U.S. Navy has experienced three fatal flight mishaps attributable to hypoxia since 2001 (1,8).

Since 1941 the U.S. Navy has been providing hypoxia familiarization training to its aviators and aircrew using low-pressure chambers (LPC; 15). Aside from small

modifications to LPC profiles, this training has not changed significantly in more than half a century. In general, Navy LPC training consists of a single exposure to 7620 m (25,000 ft) of simulated altitude. While at altitude students remove their oxygen masks for a maximum of 4 min while they perform simple psychomotor skills, complete puzzles/worksheets, or perform some other activity to help them experience and recognize the signs and symptoms of hypoxia. Following initial training during preflight indoctrination, naval aircrew return every 4 yr to receive refresher hypoxia recognition training (3).

Although the effectiveness of hypoxia familiarization training has not been well studied, the U.S. Navy has employed the LPC for more than 60 yr as its standard for training aviators to recognize and recover from acute hypoxia (7,15). While seemingly effective, hypoxia training in an LPC does have its drawbacks and limitations. First, while the probability of suffering a significant injury during or following exposure to altitude is low, medical risks do exist. These include decompression sickness and barotraumas, which could result in the grounding of an aviator for days, weeks, or in extreme cases, permanently. Second, hypoxia training in an LPC is a highly artificial environment in that students do not perform activities and experience hypoxia in the context of their normal working environment—the aircraft (6).

Recently, a number of authors have analyzed incidents of hypoxia in their respective services and have identified the need to examine alternative ways to provide dynamic hypoxia training (2,8). A review of Naval

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Safety Center aircraft hazard and mishap reports from 1980 to 2002 revealed that a large percentage of tactical jet hypoxia incidents were categorized as “mask-on” hypoxia. In fact, of the nine incidents that occurred from 1991 to 2002 in aircraft flying with onboard oxygen generating systems, all occurred in aircrew who were wearing oxygen masks at the time of the incident (8). These data are similar to a recent study by the Royal Australian Air Force which found that 63% of all hypoxia incidents over an 11-yr period were the result of oxygen regulator failure, connection failure, mask leak, or other mask problems (2). Likewise, in a much earlier review of all U.S. Air Force hypoxia incidents from 1970 to 1980, researchers found that 64.7% of those incidents occurred in aircrew using oxygen equipment and wearing an oxygen mask at all times (11). In response to the obvious threat posed by mask-on hypoxia, both the U.S. and Australian reports made specific recommendations to consider including mask-on hypoxia training for aircrew.

In 1999 researchers at the Naval Aerospace Medical Research Laboratory developed a device that can induce hypoxia using mixed gas delivered through a standard aviator’s oxygen mask. The reduced oxygen breathing device (ROBD) simulates the diminished oxygen present at altitude by mixing breathing air and nitrogen under sea level (normobaric) conditions. Initial research with early versions of the ROBD demonstrated that the device could reliably reproduce the cognitive and physiologic effects associated with hypoxia at sea level in human subjects (12,13). In 2004 Vacchiano, Vagedes, and Gonzalez conducted a study to compare the cognitive, physiologic, and subjective effects of sea level (ROBD) and reduced barometric pressure (LPC) induced hypoxia (14). The results of their seminal work indicated that the objective and subjective effects of decreasing tissue oxygenation are equivalent regardless of whether this decrease is produced at sea level with the ROBD or at reduced barometric pressure with the LPC. These results are similar to those of Westerman, who concluded that using a reduced oxygen gas mixture and delivery system to simulate 7620 m (25,000 ft) of altitude is a safe and effective way to train and familiarize aviators with the effects of hypoxia (16).

In response to the limitations inherent to the LPC and the upward trend in hypoxia incidents in naval aviation, the Naval Survival Training Institute purchased a second generation ROBD (ROBD-2) in 2004 and created a mobile training team to provide dynamic hypoxia training inside aircraft simulators. The purpose of this paper is to describe this alternate hypoxia training paradigm that combines the ROBD-2 with tactical flight simulators and to present results from student surveys.

METHODS

Participants

Using the ROBD-2 in combination with F/A-18 flight simulators, 121 F/A-18 aviators received adjunctive hypoxia training. Of these, 65 (53.7%) aviators flew the Tactical Operational Flight Trainer, 34 (28.1%) flew the Operational Flight Trainer, and 22 (18.0%) flew the

Weapons Tactics Trainer. The training was conducted in accordance with Naval Aviation Survival Training Program standard operating procedures and was provided at the request of both U.S. Navy and U.S. Marine Corps operational fleet commanders (3). Subsequent to ROBD training, all students completed a 19-question, anonymous survey. Aircrew were instructed that completion of the survey was voluntary and that their anonymity would be preserved. Participants were also advised that data from the surveys would be used to improve future iterations of ROBD hypoxia instruction. The present study was exempt from Institutional Review Board approval following internal review by the Bureau of Medicine and Surgery.

Survey Content

The survey was designed to assess whether or not the students valued the training and if they felt it was relevant to their work (5). Quantitative data was collected on demographics, flight time, number/type of experiences with in-flight hypoxia, and number of previous LPC training exposures. Qualitative data was collected on the perceived quality of ROBD training, how it compared with LPC training, hypoxic symptoms experienced during ROBD training, suggestions to improve the ROBD-simulator instruction, and how often dynamic hypoxia training should be repeated.

Device Description

The ROBD-2 (Series 6202, Environics®, Tolland, CT) is a portable, computerized, gas-blending instrument that uses thermal mass flow controllers to mix breathing air and nitrogen to produce the sea level equivalent atmospheric oxygen contents for altitudes up to 10,363 m (34,000 ft). The mass flow controllers are calibrated on a primary flow standard traceable to the National Institute of Standards and Technology. The system is equipped with an emergency dump switch that will supply 100% oxygen to subjects if/when needed.

Several features are built into the ROBD-2 to prevent over-pressurization of the crewman’s mask and to prevent reduced oxygen contents below those being requested for a particular altitude. Additionally, built-in self-tests verify all system component functionality before the operation of the system can begin. If any self-test fails the system will not operate. The ROBD-2 also includes a built-in pulse oximeter sensor that can be attached to the subject’s index finger during device use.

Training Procedures

Each aviator was individually exposed to a simulated altitude of 7620 m (25,000 ft) inside F/A-18 tactical flight simulators using the ROBD-2 while performing complex flight duties. Several simulator profiles were used, including tactical intercepts, weapons delivery, and in-flight emergencies. During the scenario, an oxygen system failure was simulated and the ROBD-2 was brought to 3048 m (10,000 ft) and then, after 2 min, was raised to 7620 m (25,000 ft). Although all students knew the purpose of the training was hypoxia recognition and recovery, students were unaware of when, during

TABLE I. RESULTS FROM CLOSED RESPONSE SURVEY QUESTIONS.

Question	yes		no	
	n	%	n	%
Have you ever experienced hypoxia in an aircraft?	19	15.7	102	84.3
Did you have safety concerns about the ROBD training today?	1	0.8	120	99.2
Did you have safety concerns about the LPC training last time you attended?	7	5.8	112	92.6
During ROBD training, were you able to recognize your hypoxia symptoms?	114	94.2	7	5.8
During ROBD training, did the simulator flight profile/scenario distract you from immediately recognizing your hypoxia symptoms?	53	43.8	66	54.5
Is the ROBD a valuable training tool for teaching pilots to recognize and recover from hypoxia?	120	99.2	0	0
Today's training objective was: "To recognize the symptoms of and treat for hypoxic hypoxia at a simulated altitude of 25,000 ft." Did ROBD hypoxia training adequately meet this objective?	119	98.3	0	0
Do you consider yourself adequately trained to cope with the emergencies associated with hypoxia?	116	95.9	3	2.5
Today you were subjected to one hypoxic exposure. Would a second (or third) exposure to hypoxia improve the training?	60	49.6	57	47.1

Note: Percentages were calculated using total aircrew surveyed (n = 121). Therefore, percentages may not total 100% due to missing responses. No more than four respondents failed to answer any question. ROBD = reduced oxygen breathing device; LPC = low-pressure chamber.

their flight, the exposure to simulated altitude would occur.

Prior to the scenario, students were instructed to describe their hypoxia symptoms and then both verbalize and perform the appropriate emergency procedures. Typically, this meant that on recognition of their symptoms, students reached for the emergency oxygen activation handle and verbalized this action, thus prompting the ROBD instructor to provide 100% oxygen through their mask. Throughout the scenarios, students' objective signs of hypoxia were monitored by a trained safety observer. Additionally, as a secondary measure, students' blood-oxygen saturation was monitored via pulse oximetry. If students' objective signs of hypoxia became overt, or if the participants' blood-oxygen saturation approached 60%, the instructor prompted them to take corrective action. Occasionally, students were too hypoxic to correctly execute emergency procedures and the instructor activated the ROBD-2's oxygen dump switch, informing the student that 100% oxygen was being delivered through the mask.

RESULTS

Sample Descriptives

The sample consisted of 121 F/A-18 aviators. Of these, 113 (93.4%) were pilots and 8 (6.6%) were Weapons Systems Officers. There were 65 (53.7%) USN and 56 (46.3%) USMC officers. Mean flight hours per participant were 1032 (SD 813.2; range 110–3700), and average number of exposures to altitude in the LPC prior to ROBD training was 1.92 (SD 1.01; range 1–5).

Student Survey Responses

The first portion of the survey was composed of several closed response, dichotomous questions that asked participants about various aspects of ROBD training. **Table I** provides a detailed description of these results. Participants were then asked about the onset of hypoxia during ROBD training compared with previous experiences in the LPC. Of the 121 aviators surveyed, 62 (51.2%) said the onset of hypoxia during

ROBD training was more insidious, 31 (25.6%) said it was less insidious, 25 (20.7%) said it was about the same, and 3 (2.5%) did not answer the question. Additionally, aircrew were asked to compare current LPC hypoxia training to ROBD training in the simulated environment. There were 117 (96.7%) aviators who rated ROBD training as more realistic than LPC training, 1 (0.8%) who said it was less realistic, and 3 (2.5%) who said it was about the same. Furthermore, 110 (90.9%) aviators rated ROBD training as more effective than LPC training, while 3 (2.5%) aviators rated LPC training as more effective than ROBD training. Eight (6.6%) aviators did not answer this question. When asked to consider current refresher hypoxia training, 66 (54.5%) aviators said ROBD training should be conducted in addition to the LPC, 53 (43.8%) said it should be conducted instead of the LPC, 0 said it should not be conducted at all, and 2 (1.7%) did not answer the question.

In the second part of the survey, participants were provided with a list of 16 symptoms of hypoxia commonly described in the literature and were asked to identify the symptoms they experienced during ROBD training. **Fig. 1** provides a summary of this data. As the figure indicates, the three most common symptoms reported were air hunger (59.4%), difficulty concentrating (51.2%), and dizziness (41.3%). The three least common symptoms reported were cold flash (1.7%), stress (2.5%), and apprehension (5.8%).

Next, students were asked how frequently ROBD training should be conducted. **Fig. 2** summarizes student recommendations. As indicated, 70 (57.9%) aviators recommended that ROBD training be conducted annually. Five (4.1%) participants did not answer the question. The final question in this section asked participants to provide an overall rating of their ROBD hypoxia training experience (see **Fig. 3**). Of the 118 students who answered the question, 111 (91.7%) rated the training as either outstanding or excellent.

The survey ended with several open response questions. **Table II** provides a summary of select aircrew comments. In general, participant comments were positive. While many felt that ROBD training was superior

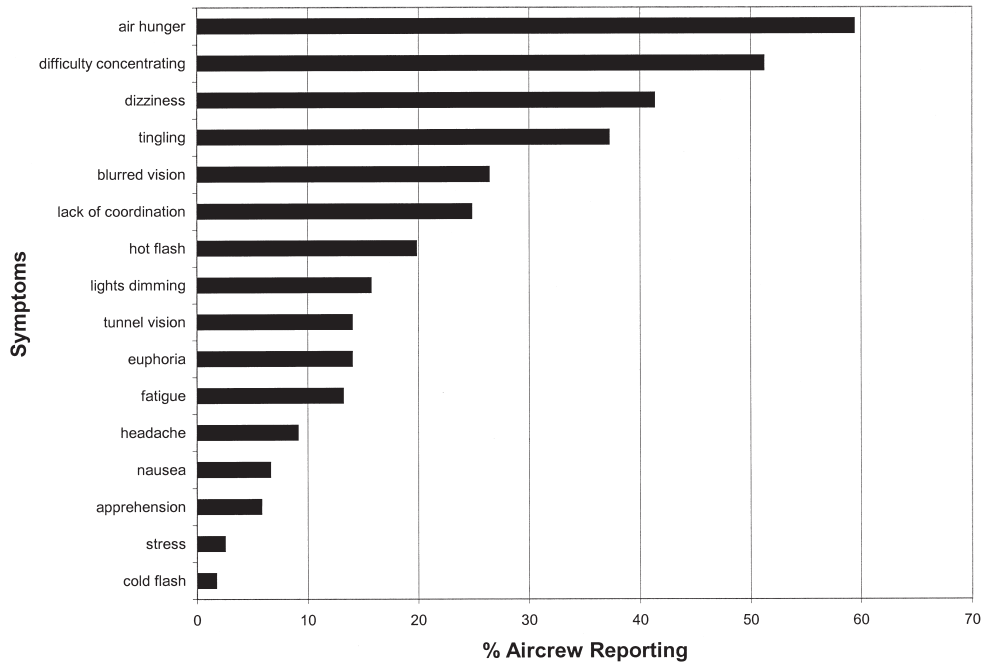


Fig. 1. Percent of total aircrew (n = 121) reporting each hypoxia symptom during ROBD training. Multiple responses possible.

to traditional LPC training, some believed that LPC training was still valuable for new aircrew who have little to no flight experience.

DISCUSSION

Limitations

Results from this subjective, self-report survey should be viewed in the context of potential reporting bias and the many uncontrolled variables inherent to the Naval Aviation Survival Training Program training

environment. Given these methodological limitations, the results of this survey must be interpreted with care. Rather than providing authoritative data, this report was designed to provide a general description of an alternate hypoxia training paradigm and present preliminary reactions from experienced aviators. If nothing else, this report identifies the need for more structured, objective scientific studies that evaluate the effectiveness of LPC and ROBD training and strive to determine which is more effective and more appropriate for different aircrew populations.

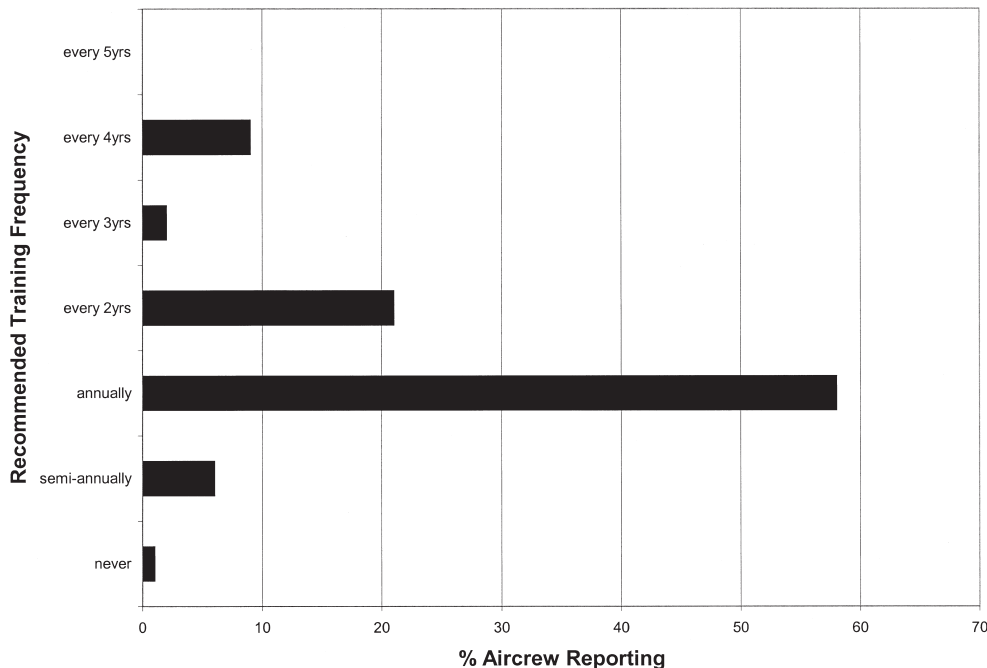


Fig. 2. Percent of aircrew answering the question: How frequently should ROBD training be conducted? Of the 121 aircrew surveyed, 5 did not answer the question.

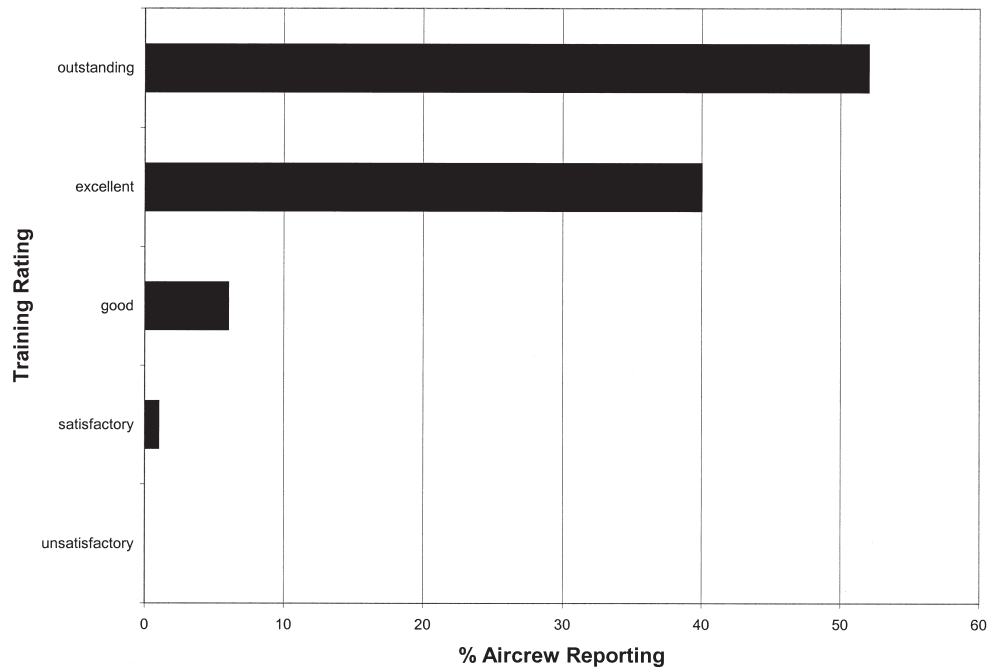


Fig. 3. Percent of aircrew answering the question: Overall, how would you rate your ROBD hypoxia training? Of the 121 aircrew surveyed, 2 did not answer the question.

Simulator Physiology

Although the training validity of experiencing hypoxia has rarely been called into question, the highly artificial environment of 18 individuals sitting in an LPC becoming hypoxic all together while performing non-flight-related tasks has been frequently cited as an area of training that could be improved (2,8,12–14,16). The concept of inducing hypoxia inside a flight simulator is not new. In the mid-1990s a group of naval aerospace physiologists proposed the idea of trying to conduct portions of the aviation physiology training program in conjunction with actual simulator events (6). This concept, known as simulator physiology (or SimPhys) was specifically targeted at experienced crewmembers (refresher students) who were well versed in their aircraft duties and who could better encode the physiological lessons into their established schemas and behavior patterns.

The training described in this report represents the realization of that original SimPhys concept—using a ROBD to induce hypoxia in a realistic flight environment. These initial survey results suggest that dynamic hypoxia training can be provided inside a flight simulator in a safe and effective manner. Furthermore, the results suggest that experienced pilots may prefer ROBD hypoxia training to LPC training for recurrent refresher training. One strong indication that the aviators surveyed valued the training is the fact that close to 60% recommended that the training be provided on an annual basis. This is a significant finding if one considers that hypoxia training in the U.S. Navy is currently only required once every 4 yr (3).

Mask-On Hypoxia Training

The idea of providing aviators with mask-on hypoxia training has probably raised more questions and con-

cerns in the naval aerospace physiology community than any other (6). For as long as hypoxia recognition/treatment has been taught, the first step in the Navy’s corrective procedure has been “go to 100% oxygen”; the assumption being that the aviator became hypoxic because they were not wearing an oxygen mask and either flew an unpressurized aircraft to an unsafe altitude, or were flying in a pressurized aircraft that lost its pressurization due to some systems or structural failure (15). Therefore, the idea of providing hypoxia training through an aviator’s oxygen mask was considered unrealistic—with some individuals suggesting that such training would result in “negative training transfer”—and thus was never given much consideration as a viable training option (6).

Currently, due to aircraft systems modifications and changes to operating procedures, the risk of experiencing mask-on hypoxia is considerable. As discussed earlier, several authors have recently reported that the majority of hypoxia incidents in tactical jet aviation have been categorized as mask-on hypoxia (2,8). Furthermore, recent data from the Naval Safety Center reveal that from 2001 to 2005 naval aviation experienced 37 hypoxia incidents, 36 of which occurred in platforms using oxygen equipment from takeoff to landing (i.e., tactical jet aviation; 9). Given this data, the type of training provided by the ROBD may in fact be of greater fidelity for tactical jet aircrew than traditional LPC training. Results from this instructional evaluation support this possibility, with more than 95% of participants rating ROBD training as more realistic than LPC training and more than 90% rating ROBD training as more effective than LPC training.

Although ROBD training appears to be a viable option for experienced tactical jet aircrew, it may not be appropriate for new students with little to no flight experience. One of the benefits of using the ROBD for

TABLE II. SAMPLING OF AIRCREW ANSWERS TO OPEN RESPONSE QUESTIONS.

Aviator Total Flight Hours	Aviator LPC Exposures	Questions/Answers
		Question: Are there any other changes you would recommend to improve ROBD hypoxia training?
1400	3	"In multicrew aircraft, put crew through training together. This would allow aircrew to experience crew coordination breakdown issues in addition to experiencing hypoxia symptoms."
2950	5	"Recommend doing two runs: one to respond as soon as symptoms are recognized, and a second to intentionally prolong the hypoxic experience to see what happens."
400	1	"Adding an emergency oxygen "green ring," a flow knob, and a control switch would be good. I've never pulled the green ring and don't know how hard to pull it or if there's any way to tell if I'd be getting oxygen when I pulled it."
405	2	"This needs to be done annually during the hour-long NATOPS check so that we don't know when it's coming."
		Question: Which hypoxia training program do you consider more effective: the low-pressure chamber version or the ROBD version you have just completed?
400	1	"They are both valuable. The chamber allows one to go further into the scenario, but the ROBD in the simulator is more realistic. The dexterity needed and decision making are great learning points and challenges."
400	1	"I was flying a simulator instead of playing patty cake. It's closer to actual flying and will help me remember what this was like in case it ever happens for real."
1650	3	"ROBD provides a realistic scenario and allows the aircrew to accurately determine symptoms and execute the appropriate procedures in an actual flight environment."
300	1	"Far more realistic. However, the LPC was also valuable for initial exposure."
350	1	"The LPC turns into a competition with your classmates to see who can go longer without air. This has a more applicable feel to it. A simulation versus a competition."
1450	2	"The opportunity to experience hypoxia symptoms in your fleet aircraft is far more valuable than a generic chamber."
		Question: Please provide any additional comments/suggestions with respect to ROBD hypoxia training.
1200	1	"The fleet needs this before more of us fly into the ground. I am more worried about flying into hypoxia than dying in combat."
2950	5	"This should be required, but we need to keep the LPC too. Younger pilots won't have the experience with the aircraft and tactics to accurately judge how much of their performance has been degraded. Super!"
450	1	"This should be mandatory training for all Hornet pilots. I would go as far as to say that this is guaranteed to save a life and jet eventually."
2100	3	"I highly encourage the further development of this training. Once every four years in the chamber is not enough. It seems in my experience an F/A-18 squadron experiences at least one hypoxia emergency a year."

ROBD = reduced oxygen breathing device; LPC = low-pressure chamber; NATOPS = Naval Air Training and Operating Procedures Standardization Manual.

hypoxia training is the ability to integrate the device with a flight simulator. Inherent to this idea is the basic assumption that the student knows how to fly the simulator and participate in interactive flight operations (e.g., controlling the aircraft, knowing systems and procedures, communicating with air traffic controllers, being able to follow flight rules and regulations, etc.). If the student has not already been trained in how to perform these flight-related tasks prior to ROBD training, the potential gains in training fidelity are lost. Moreover, there are non-hypoxia-related learning objectives that prospective aircrew students complete when participating in LPC training. These include experiencing trapped gas effects resultant from the changes in ambient pressure, performing preflight inspections, donning and operating emergency oxygen equipment, and recognizing hypoxia in other crewmembers. The inability to experience trapped gas effects alone is another reason why the ROBD may not be appropriate for indoctrination students.

In addition to the ROBD's limitations for training inexperienced student aviators, the device may not be as effective as the LPC for aircrew on multi-place aircraft. An important learning objective for this audience

is the ability to recognize hypoxia in other crewmembers. What is more, these individuals normally fly without oxygen masks donned. For these reasons, it could be argued that mask-on hypoxia training is lower in physical, functional, technical, and perceived fidelity for this population and, therefore, is probably less effective than LPC training. Ultimately, more work is needed to determine if, when, and how the ROBD could be employed for training crews of multi-place aircraft.

Subjective Hypoxia Symptoms

The most common symptom noted during ROBD training was air hunger. One of the unique design limitations of the ROBD-2 is the rate of flow to the aviator's mask. The device used for the current training provided approximately 30 L · min⁻¹ (LPM) throughout the training profile. Students were briefed prior to each event that mask flow was lower than what they were accustomed to in the aircraft. F/A-18 aircrew use the CRU-103 regulator, which provides a flow rate of between 50–240 LPM depending on altitude and whether positive pressure breathing for G equipment is used. It is possible that some of the air hunger symptoms re-

ported were an artifact caused by the lower flow produced by the ROBD-2 as compared with the CRU-103 regulator. In the current Navy ROBD training system, a software change has been incorporated to increase mask flow to 50 LPM to help alleviate this issue. Ultimately, more research is needed to further assess potential differences between mask-on hypoxia symptoms reported by aviators during ROBD training and symptoms experienced during actual in-flight hypoxia incidents.

Summary

The results of this instructional evaluation suggest that the ROBD-2, in combination with actual flight duties, is an effective and preferred means of training experienced tactical jet aviators to recognize and recover from hypoxia. Although preliminary, these results also indicate that the ROBD-2 is a safe, versatile training device for providing realistic hypoxia training inside a flight simulator. Ultimately, more structured, empirical work is needed if the overall effectiveness of ROBD vs. LPC training is to be quantified and the appropriateness of ROBD training for aviators flying non-tactical aviation platforms is to be assessed. Once these issues have been resolved, additional considerations such as required level of simulator fidelity, training flight mission profiles, and recurrent training intervals will all need to be addressed before LPC training is completely dismissed as being obsolete for experienced tactical jet aviators.

HISTORICAL NOTE

Rebreather systems were used to demonstrate and study hypoxia at ground level in the very early days of aviation. During World War I, the U.S. Army tested pilots' responses to hypoxia using a closed system with CO₂ absorption in which the subject's respiration gradually lowered the partial pressure of oxygen to simulate altitudes of up to 22,000 ft.; psychomotor tests were sometimes performed at the same time (1). In the UK, Flack used essentially the same system as the Americans (3), while Dreyer simulated altitudes of up to 18,000 feet by adding nitrogen to the inspirate (2). As aircraft flew at higher altitudes and oxygen systems were installed in cockpits, training migrated to altitude chambers run by specialists at aeromedical centers. As indicated by this article, ground-level hypoxia is now getting renewed consideration. The Editor thanks Drs. S. R. Mohler and T. M. Gibson for their input to this note.

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of the Navy, Department of Defense, nor the U.S. Government. Portions of this manuscript were presented at the 76th Annual Meeting of the Aerospace Medical Association, May 9-12, 2005, Kansas City, MO. Trade names of products of commercial or non-government organizations are cited as needed for precision. These citations do not constitute official endorsement or approval of the use of such commercial products.

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