Federal Aviation Administration

DOT/FAA/AM-15/15
Office of Aerospace Medicine
Washington, DC 20591

A Study of Protection Provided by General Aviation Oxygen Masks With Open Ambient Ports in Toxic Environments

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August 2015

Final Report

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM-15/15		

4. Title and Subtitle	5. Report Date
A Study of Protection Provided by General Aviation Oxygen Masks With Open Ambient Ports in Toxic Environments	Auugust 2015
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Paskoff LN, Mandella JG, Self DA	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
FAA Civil Aerospace Medical Institute P.O. Box 25082 Oklahoma City, OK 73125	11. Contract or Grant No.
12. Sponsoring Agency name and Address	13. Type of Report and Period Covered
Office of Aerospace Medicine Federal Aviation Administration 800 Independence Ave., S.W. Washington, DC 20591	14. Sponsoring Agency Code

15. Supplemental Notes

16. Abstract

Air transport of medical specimens aboard general aviation aircraft frequently utilizes dry ice for preservation. The sublimation of carbon dioxide (CO_2) within the confined space of the aircraft cabin, without sufficient outside air turnover, presents a potential hazard. Aircraft equipped with oxygen systems utilizing modified clinical masks that allow oxygen to be diluted with air drawn in through side ports may not offer adequate protection from CO_2 contamination.

Methods. Experiment 1. A simulated aircraft cockpit and cabin area was constructed. Total volume was approximately 3.956 m^3. Ten insulated biological specimen bags (12 x 17 x 20 in) that conformed to Department of Transportation regulations were filled with 5 lb of dry ice chips. This ratio of specimen bags to cabin volume reflected common industry practices. Air flow through the mock-up was set at a turnover rate of 9.73. CO_2 levels were monitored with mass spectrometry.

Experiment 2. A face mask with re-breather bag delivered aviator's oxygen at a flow rate of 3 Lpm and was fitted to a test mannequin head connected to two breathing machines that produced alternately an inhalation of mask contents, and then an exhalation of either ground level alveolar air (78.5% N_2, 16% O_2, 5.5 % CO_2), or alveolar air resulting from breathing 100 % O_2 (N_2 removed). The breathing machines delivered a physiological breath pattern with a tidal volume of 0.92 L at a rate of 20 breaths per minute (bpm). The head was inside a 0.76 m^3 partially sealed box. CO_2 content in the box was gradually increased and the inhaled and end tidal gas compositions were measured.

Results. Experiment 1. Carbon dioxide levels reached a mean average of 2.02% after 12 min, and then stabilized. Experiment 2. Inhaled partial pressures of CO_2 inside the mask were 5.496 mm Hg (ambient= 0.1%); 20.93 mm Hg (ambient = 2.44%); and 34.36 mm Hg (ambient= 4.75%).

Discussion. These results suggest that general aviation carriers may be creating levels of CO_2 in small airframe general aviation cabins with high densities of biological specimen bags that exceed the Occupational Safety and Health Administration and Federal Aviation Administration standards (0.5%). Further, commercially available general aviation oxygen equipment may not provide aircrews with adequate protection in environments with high CO_2 content.

17. Key Words	18. Distribution Statement
Oxygen Mask, Carbon Dioxide, General Aviation	Document is available to the public through the Internet: www.faa.gov/go/oamtechreports

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	13	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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INTRODUCTION

Air transport of medical specimens aboard general aviation aircraft frequently requires the use of dry ice to preserve specimens. Dry ice is the solid form of carbon dioxide (CO_2). The sublimation of CO_2 within the confined space of the aircraft cabin without sufficient outside air turnover presents a potential hazard for the aircrew.

A frequently employed countermeasure has been to equip the aircraft with oxygen equipment using a modified version of clinical masks that allow a mixture of 100% oxygen diluted with ambient air drawn in through an open side port. It is unknown if this equipment provides adequate protection from CO_2 contamination.

Although CO_2 is limited to a concentration in transport category aircraft of 0.5 percent by volume under Title 14 of the Code of Federal Regulations (CFR) §25.831, general aviation aircraft flying under Title 14 of the Code of Federal Regulations (CFR) Part 91 have no limitations. In fact, they are permitted to fly with an unlimited quantity of dry ice as cargo regardless of air turnover rates or breathing equipment installed in the aircraft (Figure 1).

Gibbons (1977) conducted tests using dry ice in general aviation aircraft. In these tests, paper bags were filled with dry ice and left in a closed aircraft, and the decline in mass of the dry ice was documented. Further testing examined the use of CO_2 fire extinguishers with subjects donning oxygen masks. However, no testing of the impact of dry ice sublimation on oxygen mask in-flight performance was conducted.

Maykoski (1968) noted that general aviation pilots had several suspected CO_2 contamination incidents but were reluctant to report them. In one such instance, a pilot had to don an oxygen mask and use 100% oxygen; but thought the condition was due to food poisoning. Two documented instances from this report mentioned an aircraft that was closed up for several hours and caused several crew members to experience carbon dioxide poisoning. Another incident involved a Military Airlift Command aircraft carrying frozen dinners packed in dry ice.

High CO_2 levels within aircraft cabins have been previously documented. In 1948, two commercial airliner flights required the activation of carbon dioxide-filled fire extinguishers. The first one, in May, partially incapacitated the crew. The second, in June, may have contributed to the plane's fatal crash (Civil Aeronautics Board, 1948).

In another incident concerning closed doors, the National Transportation Safety Board (NTSB) reported a DC-8 in Texas had possible accumulation of carbon dioxide due to the sublimation of dry ice for a period of time (NTSB, 2001). This flight was carrying both dry ice and paint. The aircraft had been grounded for some time due to mechanical issues.

The 1998 incident in Texas (NTSB, 2001) prompted the Federal Aviation Administration (FAA) to examine sublimation rates of dry ice (Caldwell, Lewis, Shaffstall, & Johnson, 2006). Tests conducted at the FAA Civil Aerospace Medical Institute involved the use of boxes used by the toxicology laboratory to ship and receive specimens from aircraft fatalities. Dry ice was placed in these boxes and then placed inside a hypobaric chamber for several hours at 8,000 feet to simulate a standard cargo flight. Box weights were measured both before and after each simulated flight, and a rate of sublimation was determined. No measurements of carbon dioxide were taken in the hypobaric chamber.

Figure 1. FAA Hazmat Team Surveillance Team photos of a general aviation aircraft configuration for transporting medical specimens in biological specimen bags (NTSB, 2011).

Figure 2. Wreckage of N167TB after post-crash fire (NTSB, 2011).

In 2009, a fatality occurred at Teterboro airport in New Jersey (Fig. 2). The NTSB found the accident's probable cause to be pilot error (NTSB, 2011). The company that owned the aircraft (Quest Diagnostics Inc, Reading, PA) specialized in the carriage of dry ice to haul human specimens. In the NTSB docket management system concerning this accident, a document relating to the company's carbon dioxide training contains meeting minutes that mention two separate incidents involving dry ice. One concerns a departure from Gwinnett County – Briscoe airport, Georgia, and another in an aircraft departing Teterboro Airport, New Jersey. The first was possibly due to the large volume of human specimen bags blocking airflow, along with the quantity of dry ice onboard the aircraft. The other was related to the aircraft sitting on the ramp with the doors closed, allowing carbon dioxide to build up inside the aircraft.

Our work sought to address whether sublimation of dry ice contained in standard biological specimen containers in a simulated cabin environment that mimicked the Teterboro mishap aircraft, in terms of dimensions and quantity of containers, would produce elevated ambient CO_2 levels. Furthermore, we evaluated the degree to which the Precise Flight mask deployed in the Teterboro mishap aircraft (Fig. 3), allowed CO_2 to be drawn in during inhalation.

Figure 3. Oxygen bottle and attached mask with open ambient ports shown behind pilot seat from the same fleet as the Teterboro mishap aircraft (NTSB, 2011).

METHODS

Mock-up tests

The first part of the study evaluated the time course for carbon dioxide buildup in a simulated BE-58 Twin Baron aircraft cabin. We constructed an aircraft cockpit and cabin area using ¾ inch PVC pipe and covered all sides using 0.006- in thick plastic sheeting (Figs. 4 & 5). The covering of the sheeting was attached to the pipe with industrial-grade gaffer's tape. Total volume of the simulated aircraft was 3.956 cubic meters.

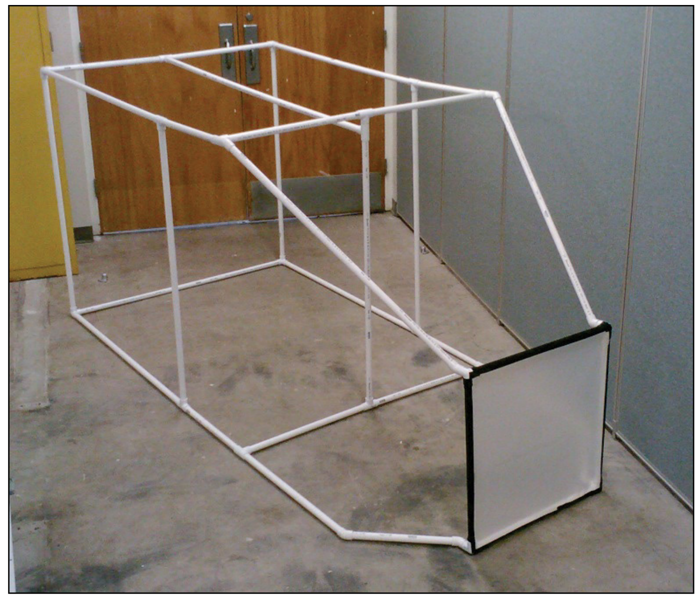

Figure 4. Skeletal structure of the cabin mockup, along with part of the skin surrounding it.

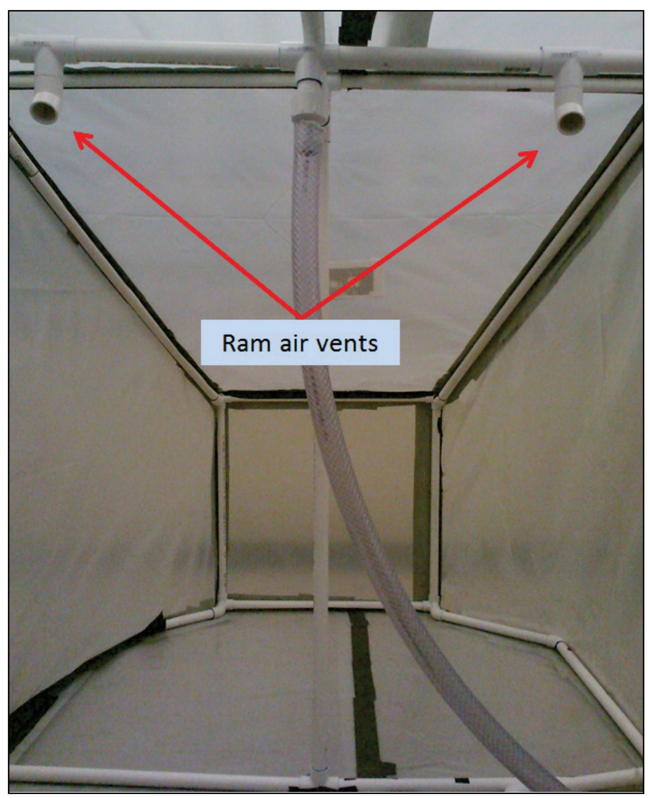

Figure 5. Internal view of the mock-up showing the ventilation system.

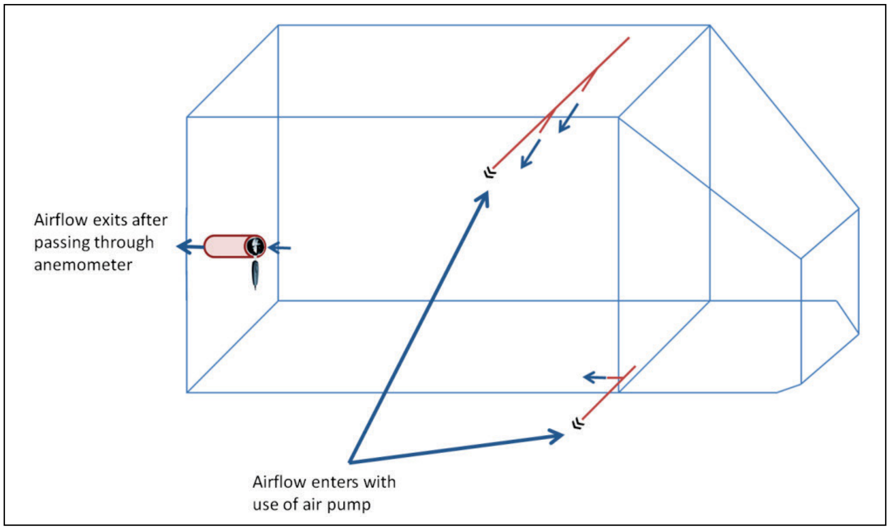

Figure 6. Location of ram air entrance, exit and placement of the anemometer.

We attempted to simulate realistic air turnover rates in the mock-up. Beechcraft documentation reported that an air turnover rate in an unpressurized aircraft like their BE-58 was unknown (Beechcraft, 2011). However, Citation aircraft with similar cabin volume report they have cabin air turnover rates ranging from 10 to 26/hr (Shelinbarger, 2015). Given that the most dangerous situation would occur in a closed aircraft parked on the tarmac (zero air turnovers/hr), with the least danger resulting from the highest turnover, we selected an intermediate rate of around 10 to test. To simulate the movement of ram air (forced air) through vents in an unpressurized aircraft, ¾-inch PVC pipes were installed and connected to a Regen Air Pump (Model R2103, Regen Air Mfg. Corp, Benton Harbor, MI). The air exited the simulated cabin through a 3-inch PVC pipe located in the rear bulkhead approximately half-way between the floor and ceiling (Fig. 6). Exiting airflow velocity was measured using a Fisher Scientific anemometer (Model 01-241; Pittsburgh, PA) placed at the exit pipe. These values were converted to volumetric flows based on the exit pipe diameter, and then to cabin air turnovers/hr based on the mock-up dimensions. To create a well-stirred environment, a 6-in fan was placed near the back of the aircraft blowing air forward. Air temperature, relative humidity, and dew point were measured using an Omega temperature humidity alarm (Model OM-THA2; Omega Engineering, Inc.; Standford, CT).

Ten biological specimen bags, used for this research on loan from Quest Diagnostics (12 in x 17 in x 20 in; Figs. 7 & 8) were each filled with 5 lb of dry ice chips and placed in the mock-up cabin. The bags had two ventilation ports on the top to satisfy ventilation requirements of 49 CFR Part 173.217. CO_2 levels in the cabin were continuously recorded over time. Two air turnover rates (9.73 and 10.58 turnovers/hr) were used throughout the 34 min that CO_2 levels were measured.

Figure 7. Typical bags used for the transport of biological specimens.

Figure 8. Biological specimen bags each filled with 5 lb of dry ice chips placed inside the mock-up cabin.

Mask Tests

To evaluate the extent to which the Precise Flight mask deployed in the Teterboro mishap aircraft allows ambient air containing a high CO_2 content to enter, we constructed a novel breathing system that utilized two flow-volume simulators (Series 1120 Hans Rudolph; Shawnee, KS). Connected together (Fig. 9), they produced alternately an inhalation of either mask contents or of ambient air and then an exhalation of alveolar air (78.5% N_2, 16% O_2, 5.5 % CO_2) delivered from a custom mixed gas cylinder into a reservoir bag that the exhalation breathing simulator drew from.

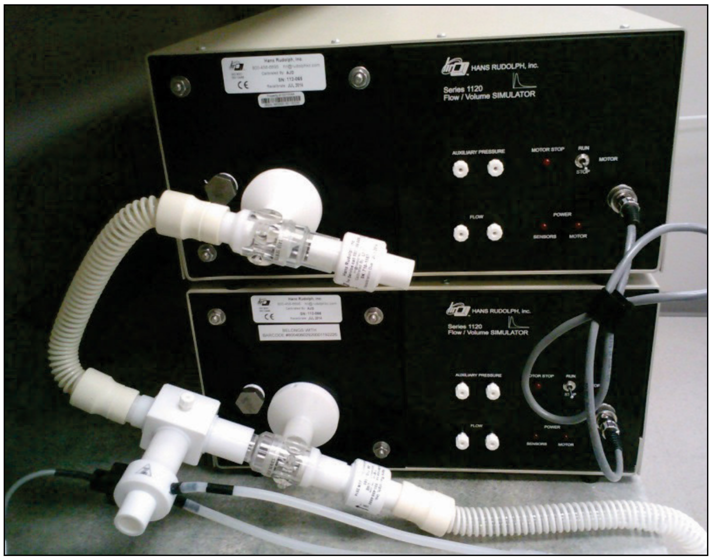

Figure 9. Two flow-volume simulators connected together such that one inhales ambient air and the other exhales simulated alveolar gas.

Appropriate directional air flow through the system was established with one-way valves. The simulators delivered a physiological breath pattern and allowed tidal volume, respiratory rate, dead air space, and functional residual capacity (FRC) to be preset (Fig. 10).

The generated air flow was "inhaled" and "exhaled" from a research head (Hans Rudolph model DR1299) fitted with an oxygen mask (Precise Flight model 020N0002-1; Fig. 11) via a simulated trachea (total dead air space=170 ml). The mask was a modified version of the Teleflex-Hudson RCI face mask, model 1009 (Fig. 12). The changes in this mask made by Precise Flight Inc. for general aviation use included the removal of two check valves: one on the side and one connecting to the rebreather bag.

Figure 11. Hans Rudolph Research Head.

Figure 12. Precise Flight Mask.

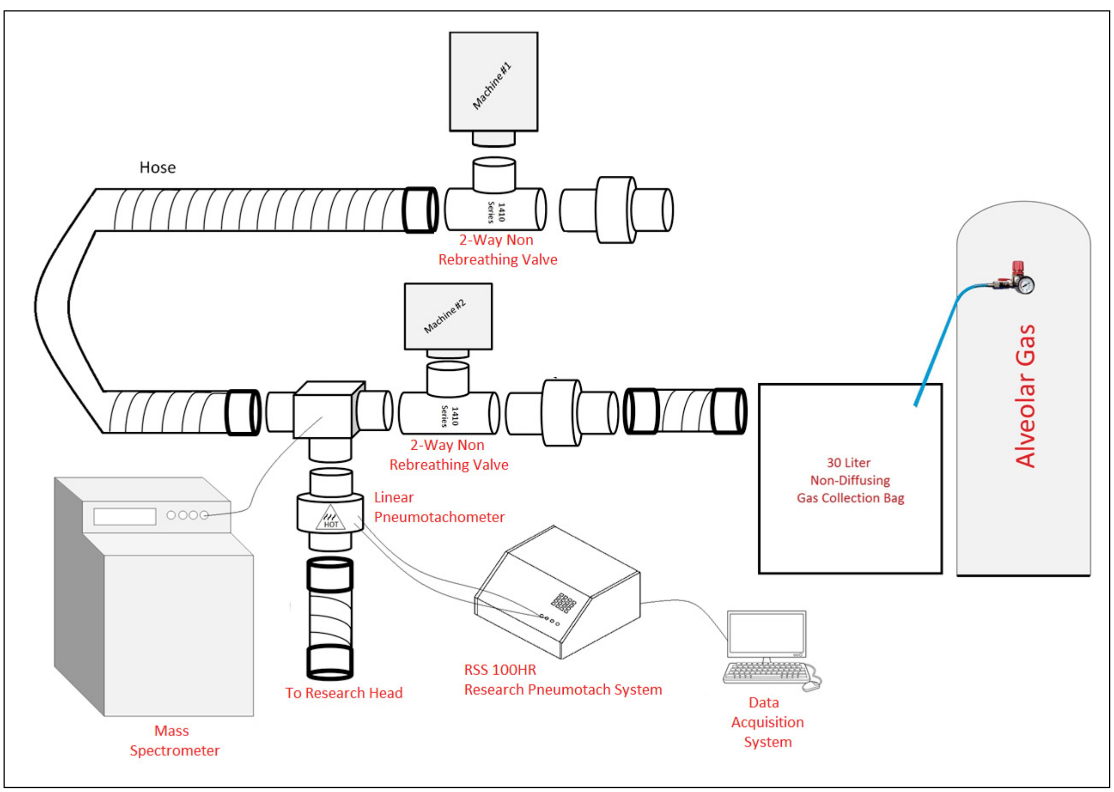

Figure 10. The breathing system circuit.

The removal of these valves allowed the individual's breath to enter the rebreather bag, mix with 100% oxygen, and permitted ambient air to enter the mask during inhalation.

Between the oxygen mask and source of 100% aviator's oxygen was an In-Line Dual Scale Flowmeter (Model A-5, Precise Flight Inc; Bend, OR; Fig. 13). To create an enclosed environment that simulated a small aircraft cabin area, the research head was placed inside a well-stirred 27 cubic foot clear plastic box into which CO_2 was injected (Fig. 14). The box vented outward such that barometric pressure was maintained at ground level.

The Precise Flight general aviation oxygen mask was attached to the research head, as seen in Figure 11, and a capillary tube from a mass spectrometer was inserted into one of the small port holes on the side of the mask. A pneumotachometer (Hans Rudolph, 3700 series, 0-160 Lpm) was placed proximal to the trachea (Fig. 14) to measure gas flow (L/min). A Perkin-Elmer Medical Gas Analyzer, MGA-1100 (Perkin-Elmer Life and Analytical Sciences, Inc.; Waltham, MA), was utilized for real-time measurement of the percentages of atmospheric gases (N_2, O_2, CO_2, and H_2O) passing into and out of the mask, and the ambient air composition within the box. Voltage output linearity was 0.5% of full scale for all gasses. Two-point calibrations were performed before each experiment using room air and a certified calibration gas (3% CO_2, 0% O_2, 97% N_2; ± 1%).

The Society of Automotive Engineers Aerospace Standard 1224B (SAE AS1224B) requires CO_2 exclusion performance testing of continuous flow aviation oxygen masks to have a breathing rate of 20 breaths per minute (BPM) with a displacement of 750 mL/cycle. The breathing machine was set to 20 (BPM) and a tidal volume of 920 mL to allow for the added dead air space of our research head-trachea circuit.

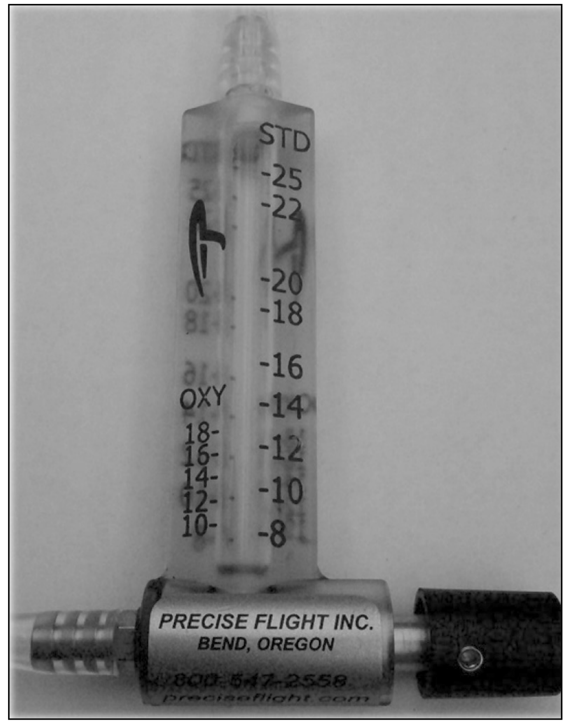

Figure 13. Precise Flight Flowmeter.

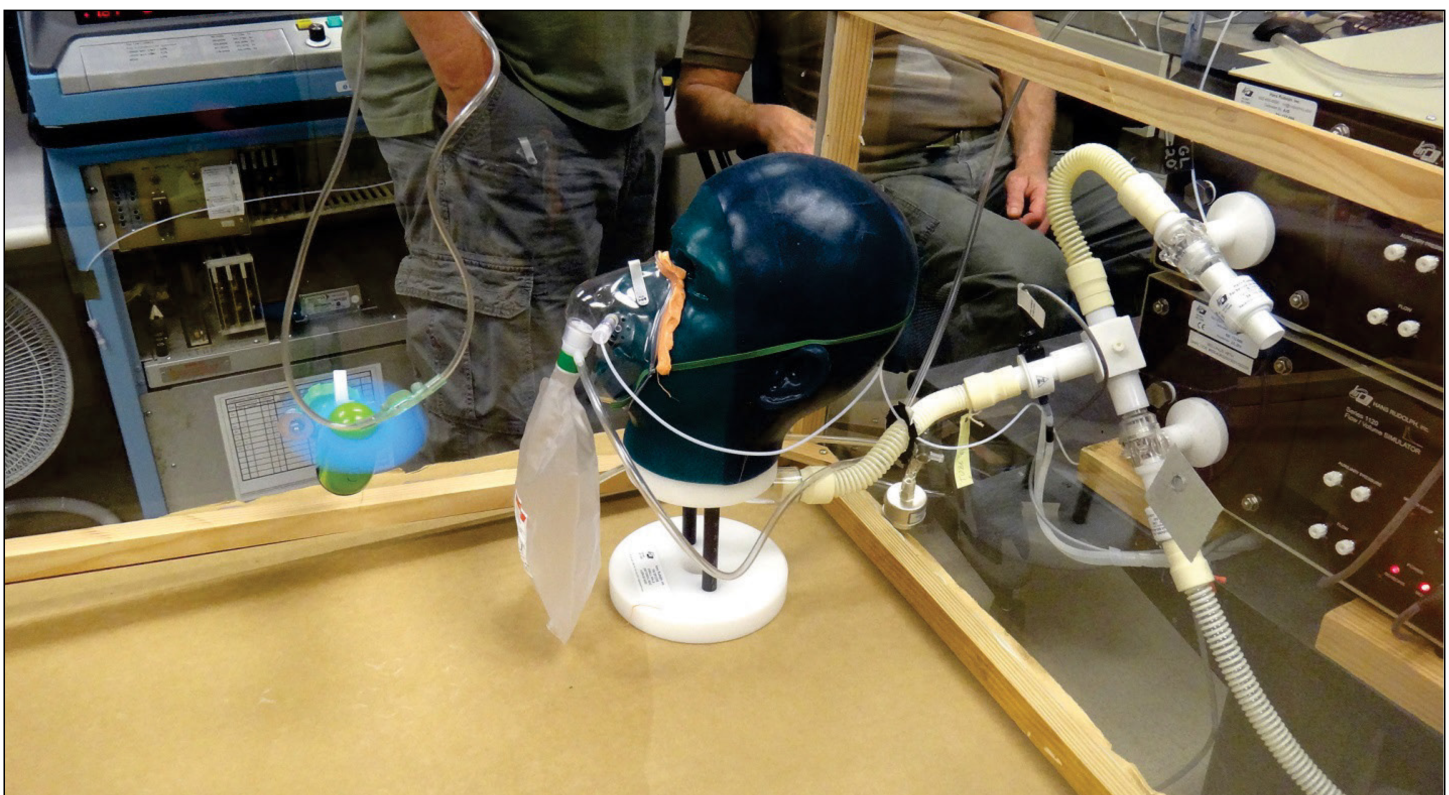

Figure 14. Configuration of the oxygen mask testing apparatus.

Table 1. Values for O_2 and CO_2 tensions during baseline performance of the breathing simulator.

	CO_2	O_2
Inhaled gas	2.084 mm Hg	152.437 mm Hg
End tidal gas	29.374 mm Hg	128.938 mm Hg

Table 2. Sequential measurements of gas composition, temperature, dew point, and relative humidity in the mock-up under 2 air turnover values.

Time (Min)	O_2 (%)	CO_2 (%)	N_2 (%)	Temp (°C)	Dew Pt. (°C)	Rel. Humidity (%)	Air Velocity (m/s)	Complete Cabin Air Turnover/hour	Barometric Pressure (mm Hg)
0	20.6	1.45	77.1	23.3	8.1	52.3	2.2	9.31	735.33
2	20.6	1.6	76.9	23.3	8.3	52.6	2.3	9.73	735.39
4	20.6	1.69	76.8	23.5	8.2	52.7	2.3	9.73	735.33
6	20.6	1.78	76.8	23.5	8.1	52.6	2.3	9.73	735.33
8	20.6	1.83	76.7	23.5	8.0	52.6	2.3	9.73	735.33
10	20.5	1.88	76.7	23.6	7.9	52.5	2.3	9.73	735.33
12	20.6	2.02	76.6	23.6	7.8	52.5	2.3	9.73	735.33
14	20.5	2.2	76.5	23.6	7.8	52.5	2.3	9.73	735.33
16	20.6	2.1	76.6	23.6	8.0	52.7	2.3	9.73	735.39
18	20.5	2.25	76.4	23.6	8.0	52.6	2.5	10.58	735.39
20	20.5	2.15	76.5	23.6	8.2	53.1	2.5	10.58	735.39
22	20.5	2.07	76.5	23.7	8.2	53	2.5	10.58	735.39
24	20.6	2.1	76.5	23.7	8.2	53	2.5	10.58	735.39

Baseline performance of the system in room air with a ground-level alveolar gas mixture was characterized without the mask in place. For this, the mass spectrometer sampling line was placed just inside the mouth. Values for O_2 and CO_2 are presented in Table 1.

Next, the mask was attached to the head, and the margins in contact with the face were sealed with tacky wax. The oxygen system flow regulator was set at 3 Lpm. An in-line pneumotachometer (Hans Rudolph, 8411 series, 0-10 Lpm) reported that this created a flow of 3.43 Lpm. The alveolar gas composition used was switched from a ground level ambient air composition to one that simulated a pilot breathing on a mask suppling 100% oxygen (N_2 component removed).

A simulated scenario of dry ice sublimation was created by slowly pumping carbon dioxide into the cabin box. As carbon dioxide levels within the box rose, inhaled and exhaled gas composition was measured through the mass spectrometer sampling line connected to the mask.

Analog signals from all monitoring equipment were digitized at 20 samples/s and recorded with a custom-built LabView data acquisition instrument (National Instruments Corp.; Austin, TX).

RESULTS

Mock-Up Tests

We evaluated the degree to which CO_2 would build up over time in a ventilated space that mimicked the Teterboro mishap aircraft cabin. We investigated a scenario where the mock-up contained 10 specimen bags, each containing 5 lb of dry ice chips. CO_2 levels were measured under two cabin air turnover rates (Table 2).

Carbon dioxide levels climbed to 2.2% over 16 min, with a 9.73 turnover rate. The CO_2 levels appeared to stabilize following an increase in air turnover rate to 10.58, suggesting that this high turnover rate was required to prevent CO_2 accumulations.

Mask Test

We tested the degree to which the Precise Flight mask was able to exclude ambient CO_2. Ventilation and gas composition measurements were made with both mask OFF (Figs. 15 & 17) and mask ON configurations on the mannequin head (Figs. 16 & 17).

These results show that increases in ambient CO_2 were transmitted to the gas mixture inside the mask with an open ambient side port.

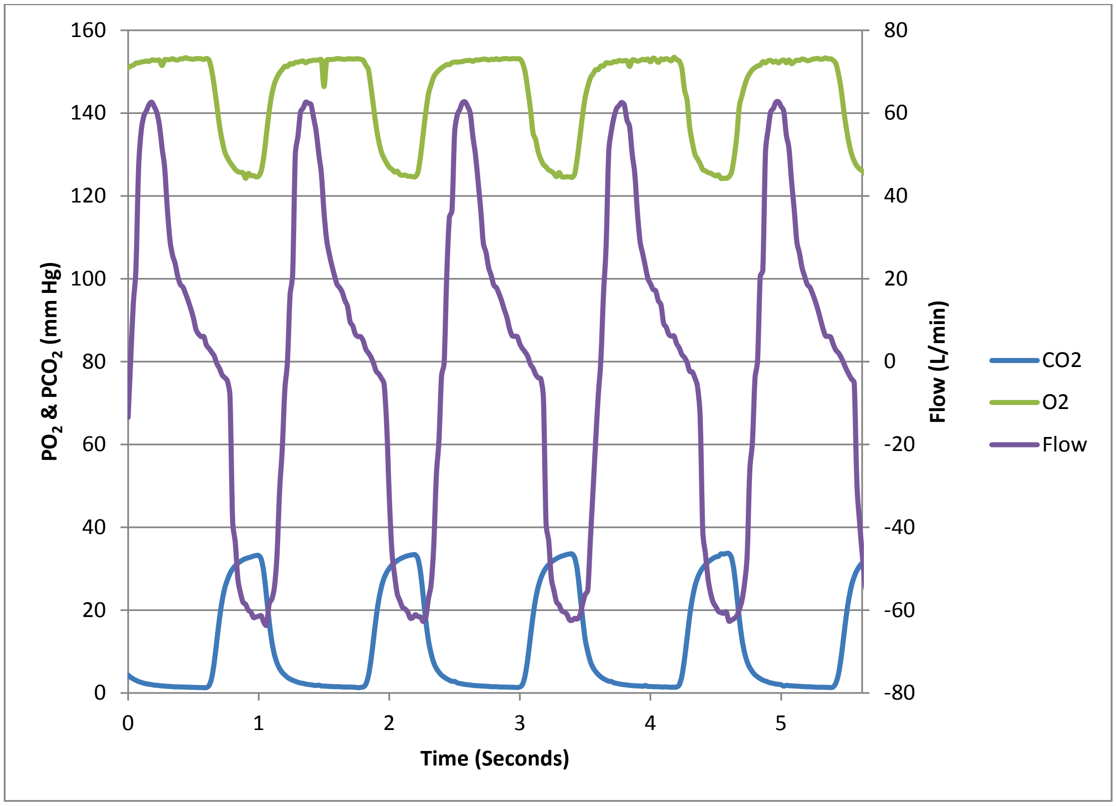

Figure 15. Mask OFF breathing ambient air at 730.694 mm Hg. Composition of the exhaled gas was 5%CO_2, 16.4%O_2, and 79%N_2.

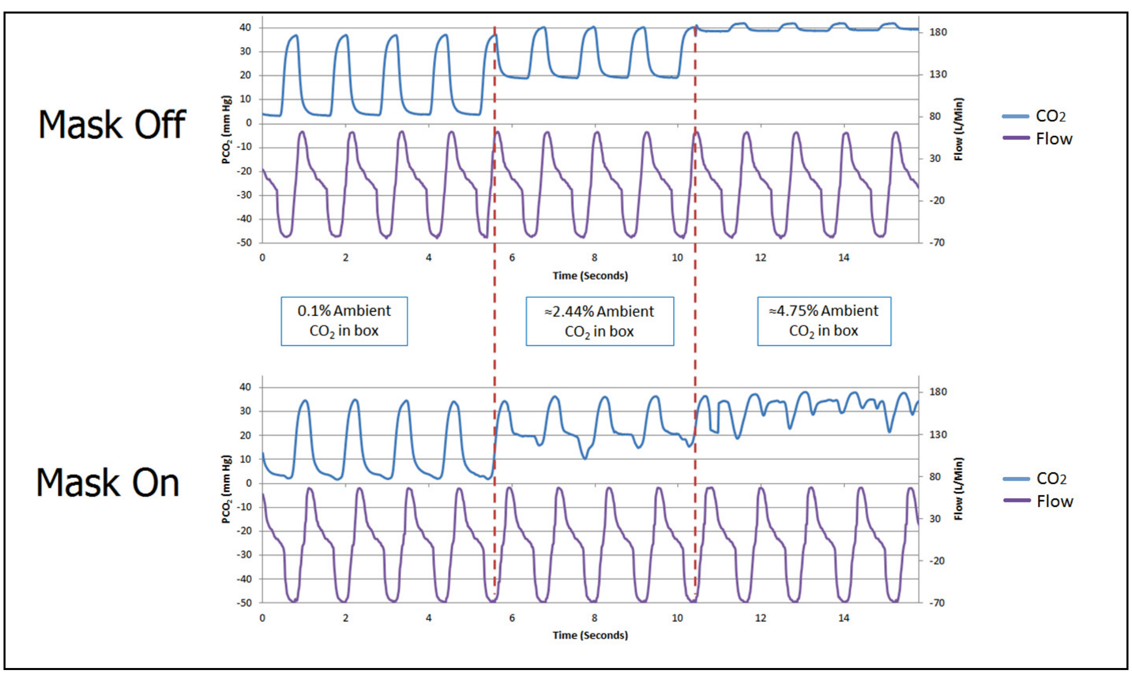

Figure 16. Comparison of rising CO_2 levels with and without a mask. As ambient [CO_2] approached that of end tidal CO_2, the directional changes in PCO_2 caused by ventilation approached nil.

DISCUSSION

This research investigated the impact of open-to-ambient ports in general aviation oxygen masks within a CO_2 contaminated cockpit environment. With the use of a breathing simulator and research head that could exhale a predetermined alveolar gas, it appears that an individual attempting to use these masks will inhale only slightly less ambient CO_2 than without a mask. This suggests that the use of this style of mask will probably offer little protection to the user.

Hunter and Olson (1988) tested the Hudson Multi-Vent oxygen mask, which was designed for clinical use. This mask was similar to the one used in the present study. They noted that location of the mask on the face was important in determining the amount of oxygen delivered to the user. Although the oxygen may be set to a maximum flow, the location of the mask on the user's face may allow oxygen flow to exit through the vents.

Brantigan (1975) tested several types of general aviation oxygen masks at varying altitudes by measuring arterial blood gases. One brand of mask, the *Hudson-type mask*, is the same type used in this present study. Although Brantigan measured end tidal PCO_2 at varying altitudes and oxygen flow rates, any ambient air inhaled consisted of the standard air at that altitude. High concentrations of carbon dioxide in the flight deck were not considered for his research, but Brantigan noted that oxygen tends to flow into the mask and out of the holes of the Hudson mask during the passive moments of respiration.

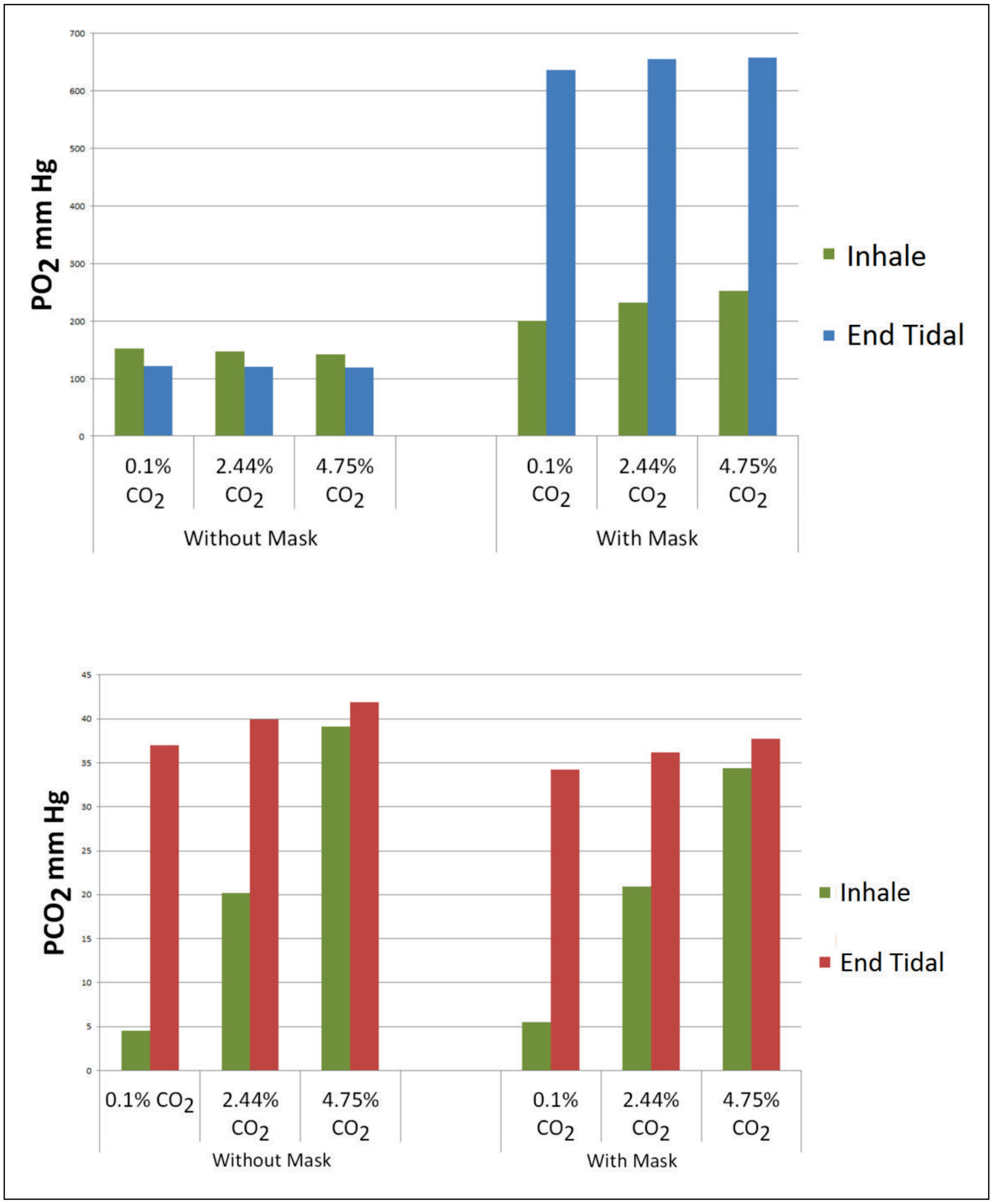

Figure 17. Inhalation and exhalation O_2 (top) and CO_2 (bottom) tensions under varying ambient concentrations of CO_2. Pb = 730.5 mm Hg under both conditions. End tidal O_2 tensions that exceeded inhaled tensions seen with the mask on are believed to be created by turbulent air flow patterns in the mask.

While describing performance characteristics of general aviation oxygen masks, McFadden, Harrison, and Simpson (1967) noted a disadvantage to constant-flow phase-dilution general aviation masks. This limitation was the inability to compensate for to the pilot's physical or emotional state. It maintained a preset flow rate regardless of demand. Testing mask performance under toxic ambient air composition conditions was not part of the testing criteria.

We have demonstrated that the masks marketed by Precise Flight that are currently deployed in some general aviation aircraft do not exclude ambient air from entering during inhalation. This dynamic, although providing adequate oxygen delivery, is unlikely to provide protection to the user in a toxic cabin environment.

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