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**CARBON DIOXIDE WASHOUT OF AN EMERGENCY BREATHING
SYSTEM MASK MODIFIED FOR USE IN THE ADVANCED SEAL
DELIVERY SYSTEM (ASDS) TRAINER**



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19. ABSTRACT (Continue on reverse if necessary and identify by block number) A modified Emergency Breathing System full face mask was evaluated for use in the Advanced SEAL Delivery System trainer. The mask contained an oral-nasal cup and two spiral-wound plastic hoses on its inhalation and exhalation openings. Each hose was six feet long with an inside diameter of 1.25 inches and had six rectangular slots cut through the hose wall. The slots were approximately eight inches from one end of each hose. Testing was conducted in an unpressurized hyperbaric chamber that was well ventilated with air. Carbon dioxide (CO ₂) washout volume - averaged inspired CO ₂ - was calculated at a respiratory minute ventilation of 22.5 liters per minute (l·min ⁻¹). The mask was ventilated with a mechanical breathing simulator. One hundred per cent CO ₂ was injected at 0.9 l·min ⁻¹ into the breathing loop. Mean CO ₂ washout was determined for two configurations: normal, with both hoses positioned so that the slotted ends are near the mask; and reversed exhaust, with inhalation hose positioned with its slots near the mask and exhalation hose positioned with the slots away from the mask. By our normalizing for the actual end-tidal CO ₂ level, the volume-averaged CO ₂ in the normal configuration was 0.71% and 0.75% with the exhaust reversed. Carbon dioxide washout of the modified emergency breathing system mask with exhaust hose in either configuration is acceptable for use in the ASDS trainer.				
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INTRODUCTION

Navy Experimental Diving Unit (NEDU) was tasked by Naval Sea Systems Command (NAVSEA) to test and evaluate the ventilatory sufficiency of a modified Emergency Breathing System (EBS) full face mask (Biomarine Inc; Exton, PA) for use in the Advanced SEAL Delivery System (ASDS) trainer.¹ The evaluation was conducted on behalf of Naval Air Systems Command (NAVAIR), Training Division, Orlando, FL.

In the ASDS during an actual emergency, a SEAL dons an EBS mask and breathes gas through two six-foot long hoses — one for inhalation and one for exhalation — connected to a manifold. Since the ASDS trainer does not have a breathing gas manifold, the original hoses are replaced with spiral-wound plastic hoses through which slots have been cut to allow the wearer to inhale from and exhale into the ASDS trainer compartment. The compartment is not pressurized and is well ventilated by an open loop air conditioning system that does not recycle the compartment atmosphere. The goal of the current study was to determine whether a SEAL wearing the modified EBS full face mask inspires safe concentrations of carbon dioxide (CO₂) during ASDS training. The mask's effect on inspired CO₂ was determined by measuring CO₂ washout — the volume-averaged inspired CO₂ — under conditions approximating those of training.

METHODS

EQUIPMENT AND INSTRUMENTATION

Test equipment was set up as shown in Figure 1. One ASDS trainer mask provided to NEDU by NAVAIR, Training Division, Orlando, FL, contained an oral-nasal cup and was modified by installing two spiral-wound plastic hoses to the mask's inhalation and exhalation openings to simulate the supply and exhaust hoses used inside the ASDS. Each hose was six feet long, with an inside diameter of 1.25 inches. Both hoses had six rectangular slots (approximately 1 inch x 3/8 inch) cut through the hose wall to allow chamber atmosphere to enter and exit during respiration. These slots were located approximately eight inches from one end of each hose and were protected from debris entry by coarse weave screen wire. The slots in the inhalation hose were always positioned 180 degrees from those in the exhalation hose.

PROCEDURES

Testing Conditions. Testing was conducted in an unpressurized hyperbaric chamber while well ventilated with air at ambient temperature (approximately 75 °F). The chamber had an internal volume of 420 cubic feet. The mask was positioned on a manikin head (Figure 2). Ventilation through the mask was achieved by attaching the head to a breathing simulator, a mechanically driven piston within a cylinder.

Carbon Dioxide Washout. CO₂ washout — volume-averaged inspired partial pressure carbon dioxide (PCO₂) in kilopascals (kPa) — and estimated dead space volume (liters) were calculated at a respiratory minute ventilation (RMV) of 22.5 liters per minute (l·min⁻¹) — i.e., 1.5 l·breath⁻¹ at 15 breaths·min⁻¹.³ The mask was ventilated with air as the medium in a mechanical breathing simulator (Reimers Consulting; Springfield, VA). Gas continuously drawn from the manikin's mouth within the oral-nasal mask was analyzed for CO₂ with an infrared absorption analyzer (Model CD-3A with a P-61B sensor and vacuum pump; Applied Electrochemistry Ametek; Pittsburgh, PA) shown in Figure 3. The delay time between the CO₂ and volume signals was determined after all data were collected. Tidal volume (liters) was determined from the breathing simulator volume signal. One hundred per cent CO₂ controlled by a mass-flow controller (Model 8274; Matheson Tri-Gas, Inc.; Montgomeryville, PA) was injected at 0.9 l·min⁻¹ (four percent of RMV) into the breathing loop.

Dead space and the average inspired CO₂ were estimated by the method of Warkander and Lundgren.³ The amount of inspired CO₂ (ACO₂) — for example, kPa·liter⁻¹ — was determined by using the equation

$$ACO_2 = \int PCO_2 \cdot dV, \quad (\text{Eq. 1})$$

where PCO₂ is the CO₂ partial pressure at the mouth. For computational reasons, the following equation was used:

$$ACO_2 = \sum PCO_2 \cdot \Delta V. \quad (\text{Eq. 2})$$

The dead space (V_d) was calculated with the equation

$$V_d = ACO_2 / P_{ETCO_2}, \quad (\text{Eq. 3})$$

where P_{ETCO₂} is the CO₂ level at the end of the expiration. The average inspired CO₂ (P_{inCO₂}) was calculated by using the equation

$$P_{inCO_2} = ACO_2 / V_T, \quad (\text{Eq. 4})$$

where V_T is tidal volume.

Additional equipment used

1. Facility data acquisition system
2. CO₂ flow transducer (Model 8272-0453; Matheson Tri-Gas, Inc.; Montgomeryville, PA)
3. Digital temperature standard (Model HH42; Omega Engineering, Inc.; Stamford, CT)
4. Calibration gases with certification:
 - a. 2.49% CO₂, balance N₂
 - b. 4.97% CO₂, balance N₂

- c. 100% CO₂
5. ± 1.0 psi oral pressure transducer (Model 289-540-001; Keller; Newport News, VA)

EXPERIMENTAL DESIGN AND ANALYSIS

Mean CO₂ washout and dead space volume were determined during five one-minute breathing periods (15 breaths) for two configurations of the exhaust hoses. The end of each hose distal to the mask was plugged and positioned approximately one foot in front and one foot above its connection to the mask.

1. Normal configuration: both hoses were positioned so that their ends with slots were near the mask.
2. Reversed exhaust: the inhalation hose was positioned with its slots near the mask, while the end of exhalation hose with the slots was positioned away from the mask.

Raw CO₂ measurements were normalized to end-tidal CO₂ = 5% by multiplying CO₂ data by the ratio of the actual end-tidal CO₂ concentration (%) divided by 5%.

RESULTS

CO₂ washout data are presented in Figures 4 through 7. For the normal hose configuration, gas sampling delay time allowed correct determination of volume-averaged inspired CO₂ and dead space volume for only two of five trials. All five trials for the reversed exhaust hose configuration could be used to determine CO₂ ventilation sufficiency. Raw volume-averaged inspired CO₂ levels were approximately 1.2%, with the end-tidal CO₂ $\approx$ 7% (Figures 4 and 5). The normalized volume-averaged inspired PCO₂ (mean $\pm$ standard deviation) levels were 0.47 ± 0.04 kPa in the normal hose configuration and 0.76 ± 0.11 kPa in the reversed (Table 1; Figures 6 and 7). The dead space of the mask, regardless of hose configuration, was estimated to be slightly less than 0.2 liter (Table 2).

DISCUSSION

The calculated dead space and CO₂ washout of the modified EBS mask are similar to the dead space of the AGA mask.³ The AGA mask, like the EBS mask, is approved for use by firefighters.

End-tidal CO₂ normally approximates 5% because of a compensatory change in ventilation to maintain the arterial CO₂ concentration around 40 mm Hg. As a result, the National Institute of Occupational Safety and Health (NIOSH) procedure for determining how a self-contained breathing apparatus affects rebreathing of expired CO₂ requires a

relatively complex breathing simulator system to produce the mandated expired gas with 5% CO₂ and inspired gas with no CO₂.^{4,5} Although the method used in the present study resulted in the raw volume-averaged inspiratory and end-tidal CO₂ concentration substantially greater than the accepted NIOSH values, the current method yields valid results by employing a much simpler breathing simulator system and a posttest adjustment of the CO₂ concentrations.

The adjustment of CO₂ concentrations can be explained by considering a snorkel filled with the last part of an exhaled breath. The calculated dead space relates the ratio of inspired amount of CO₂ to the end-tidal CO₂. If the snorkeler were to exhale twice the concentration of CO₂, then the end-tidal CO₂ would double — as would the amount inspired of CO₂. Thus, since the ratio of inspired to end-tidal CO₂ remains constant, it is not very critical what the CO₂ flow actually is. By using the concept of the constancy of the ratio of inspired to end-tidal CO₂, it is possible to calculate the average inspired CO₂ when the end-tidal CO₂ and the dead space are known. Had the CO₂ flow been reduced or the ventilation been increased to achieve 5% end-tidal CO₂ instead of the 7% in the present study, the inspired CO₂ concentration would have been only 5/7 of the raw value — i.e., about 0.9%. By normalizing the CO₂ levels, the mean volume-averaged CO₂ for the two runs with hoses in the normal configuration was 0.47% (Figure 6), and for the five runs with the expiratory hose reversed it was 0.76% (Table 1).

Using time-averaged inspired CO₂ concentration as its basis, NIOSH prescribes service times (maximum periods that the apparatus can be worn) for CO₂ concentrations up to 2.5%. Since the normalized inspired CO₂ concentration was approximately 0.9%, service time for the modified EBS mask should not exceed four hours.⁴ Our results indicate that the dead space and performance of this mask, regardless of hose configuration, does not impose significant ventilatory encumbrance on the wearer.

CONCLUSION

Ventilation for the modified EBS mask with exhaust hoses in either prescribed configuration is acceptable for use in the ASDS trainer.

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1. U.S. Naval Sea Systems Command, *Task Assignment 05-08: Evaluation of a Full-Face Mask for the ASDS Trainer*, 11 Aug 2005.
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5. E. J. Kloos and J. A. Lamonica, *A Machine-Test for Measuring Carbon Dioxide in the Inspired Air of Self-Contained Breathing Apparatus*, United States Department of the Interior, Bureau of Mines, Report 6865, 1966.

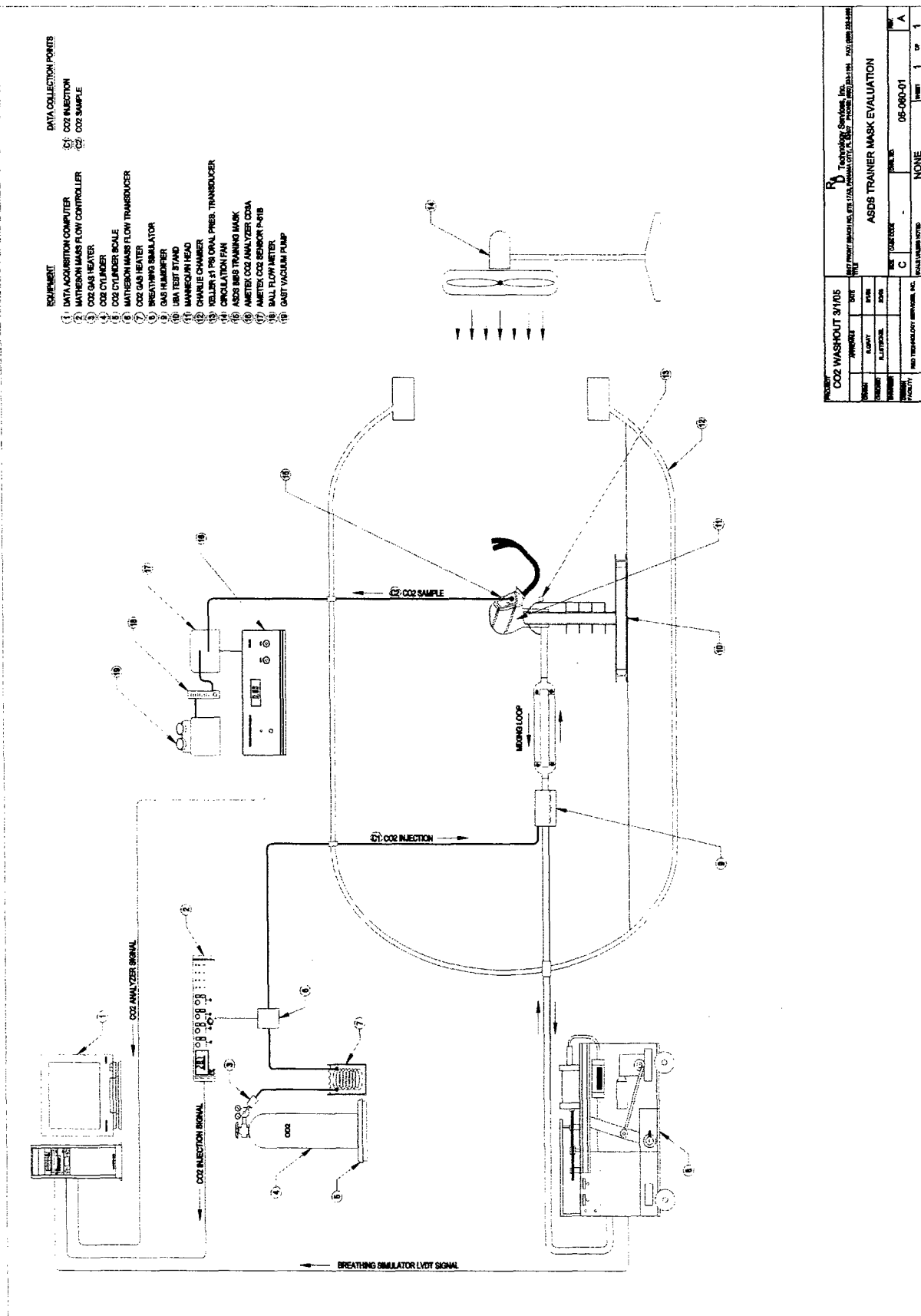


Figure 1. Test Equipment.

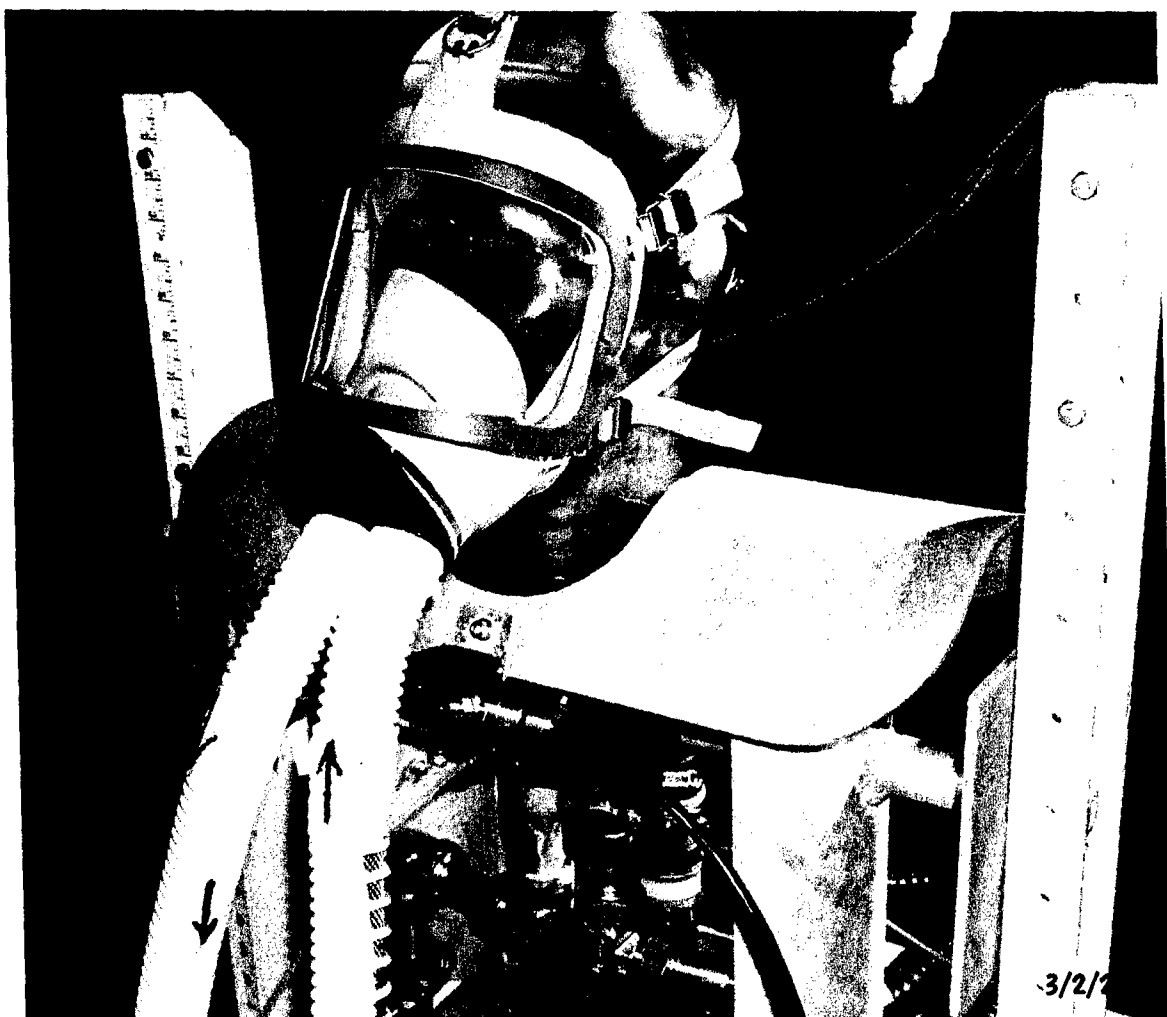


Figure 2. ASDS trainer mask positioned on a manikin head. Stainless steel pipes pass through the head and form an airway from the mouth inside the oral-nasal mask to the breathing simulator. Arrows indicate the direction of the gas flow. Slots cut through the inhalation hose are visible.

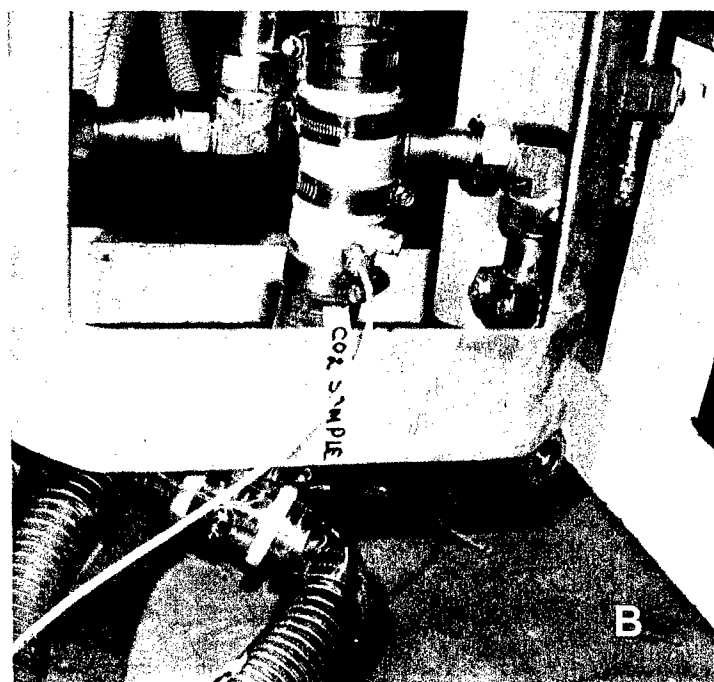
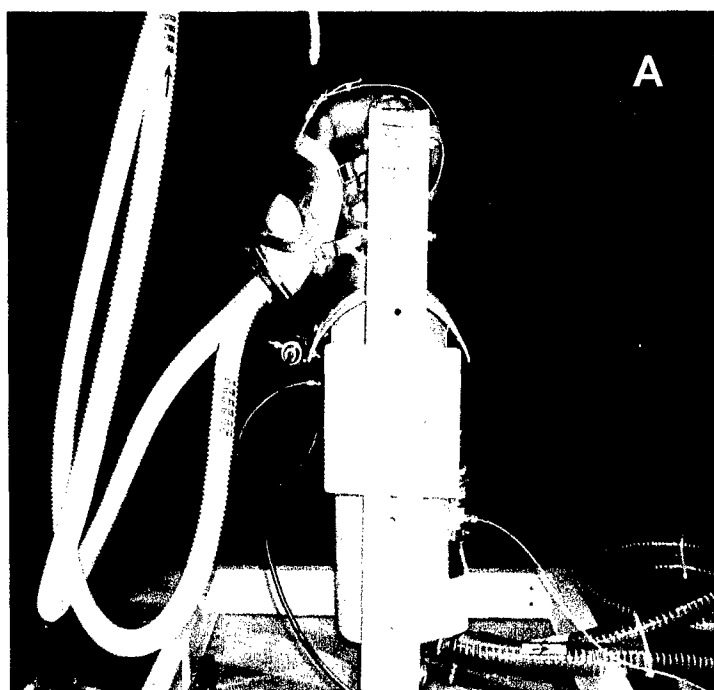


Figure 3. (a) ASDS trainer mask positioned on a manikin head. Slots cut through hoses are visible. (b) The gas sampling line enters the airway piping through a fitting at the rear and is threaded up to the mouth.

Table 1.
Normalized volume-averaged inspired CO₂ (kPa) for both mask configurations.

Mask-hose configuration	Volume-averaged inspired PCO ₂ (kPa)						
Trial	1	2	3	4	5	mean	SD
Normal	---	---	---	0.50	0.43	0.47	0.04
Reversed	0.64	0.75	0.73	0.94	0.72	0.76	0.11

Table 2.
Calculated dead space volume (liters) for both mask configurations.

Mask-hose configuration	Dead Space (l)						
	Trial	1	2	3	4	5	mean
Normal	---	---	---	0.15	0.13	0.14	0.01
Reversed	0.18	0.18	0.18	0.18	0.18	0.18	0.00

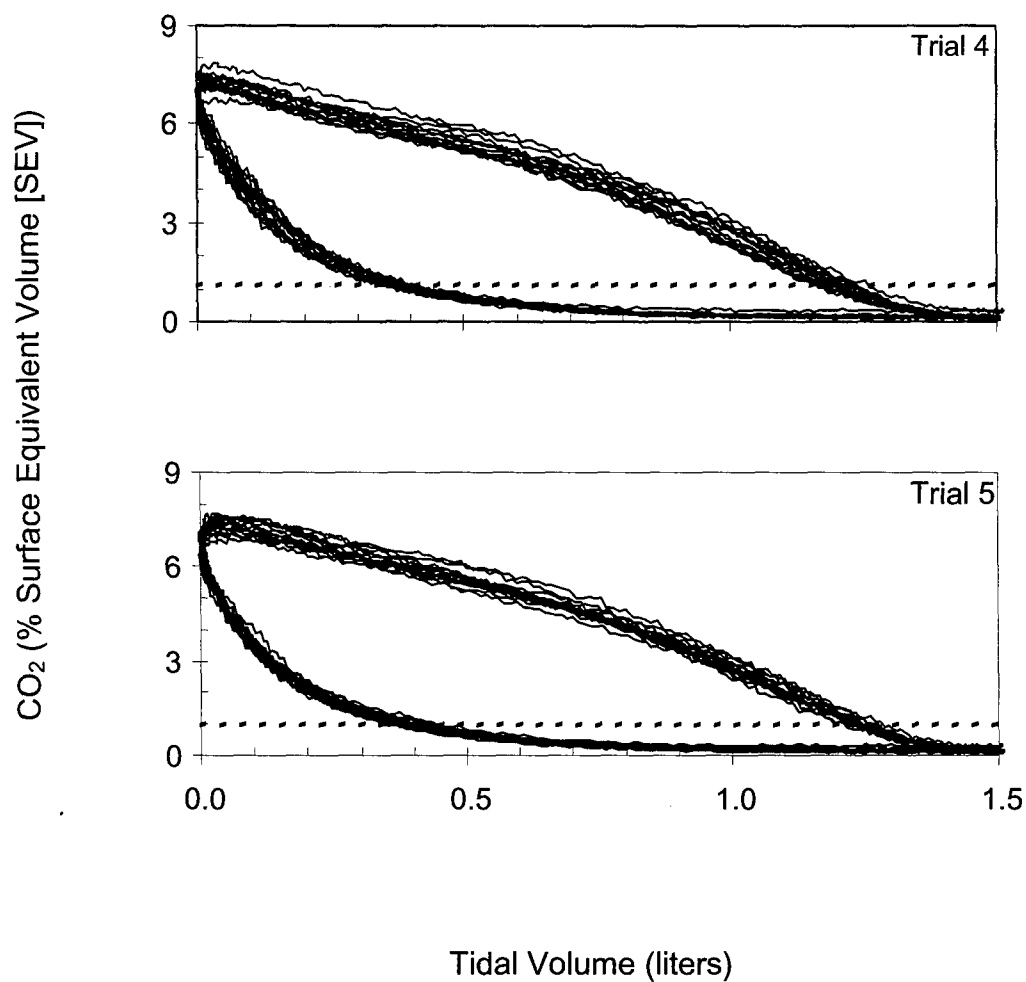


Figure 4. Raw volume-averaged inspired CO₂ of the modified EBS mask when the slots in both hoses are near the mask. The dotted line in each panel indicates the average inspired level of CO₂.

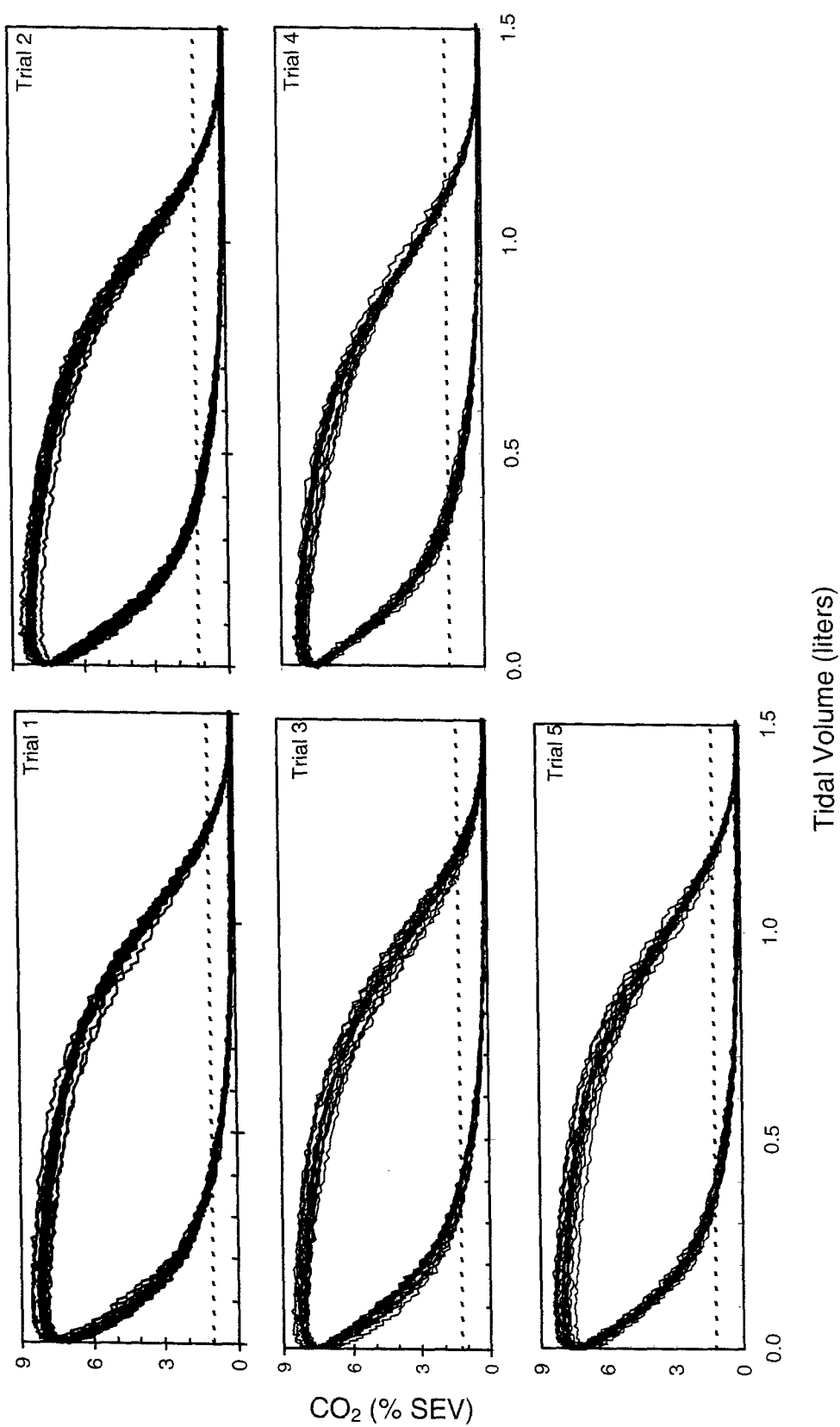


Figure 5. Raw volume-averaged inspired CO₂ of the modified EBS mask when the slots in the inhalation hose are near the mask and those in the exhalation hose are positioned away from the mask. The dotted line in each panel indicates the average inspired level of CO₂.

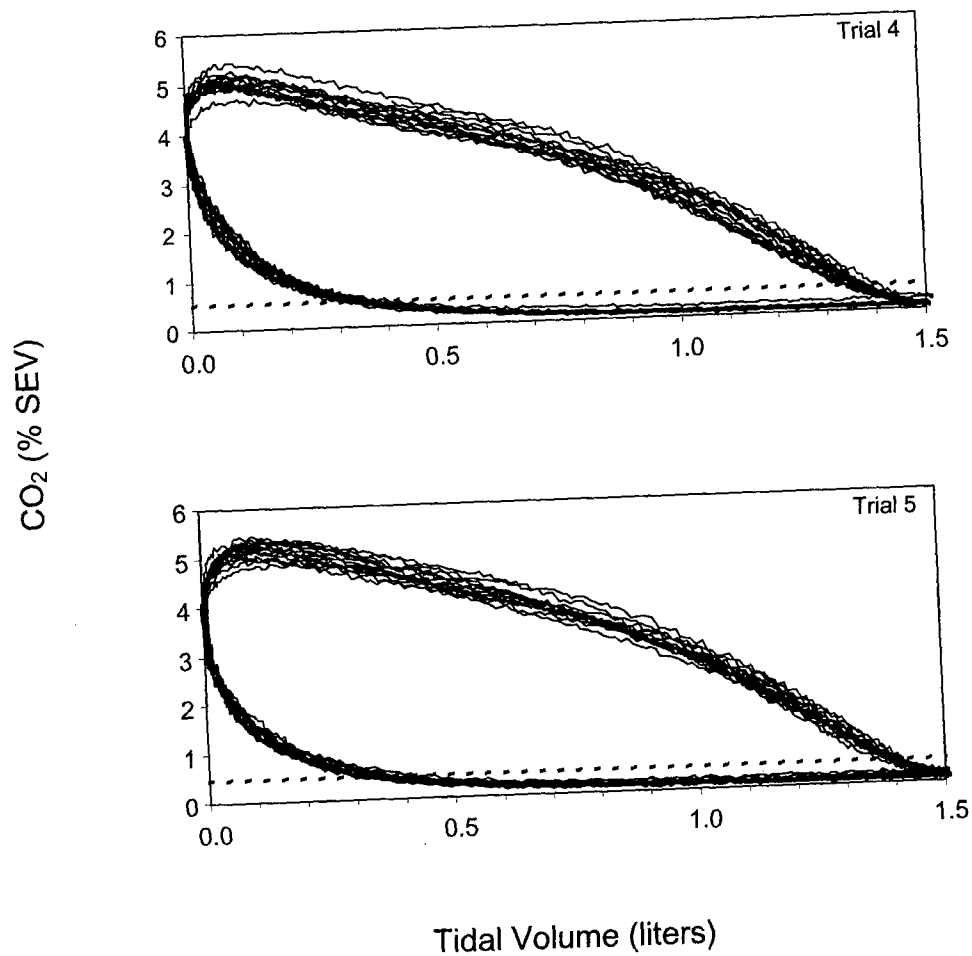


Figure 6. Normalized volume-averaged inspired CO₂ of the modified EBS mask when the slots in both hoses are near the mask. The dotted line in each panel indicates the average inspired level of CO₂.

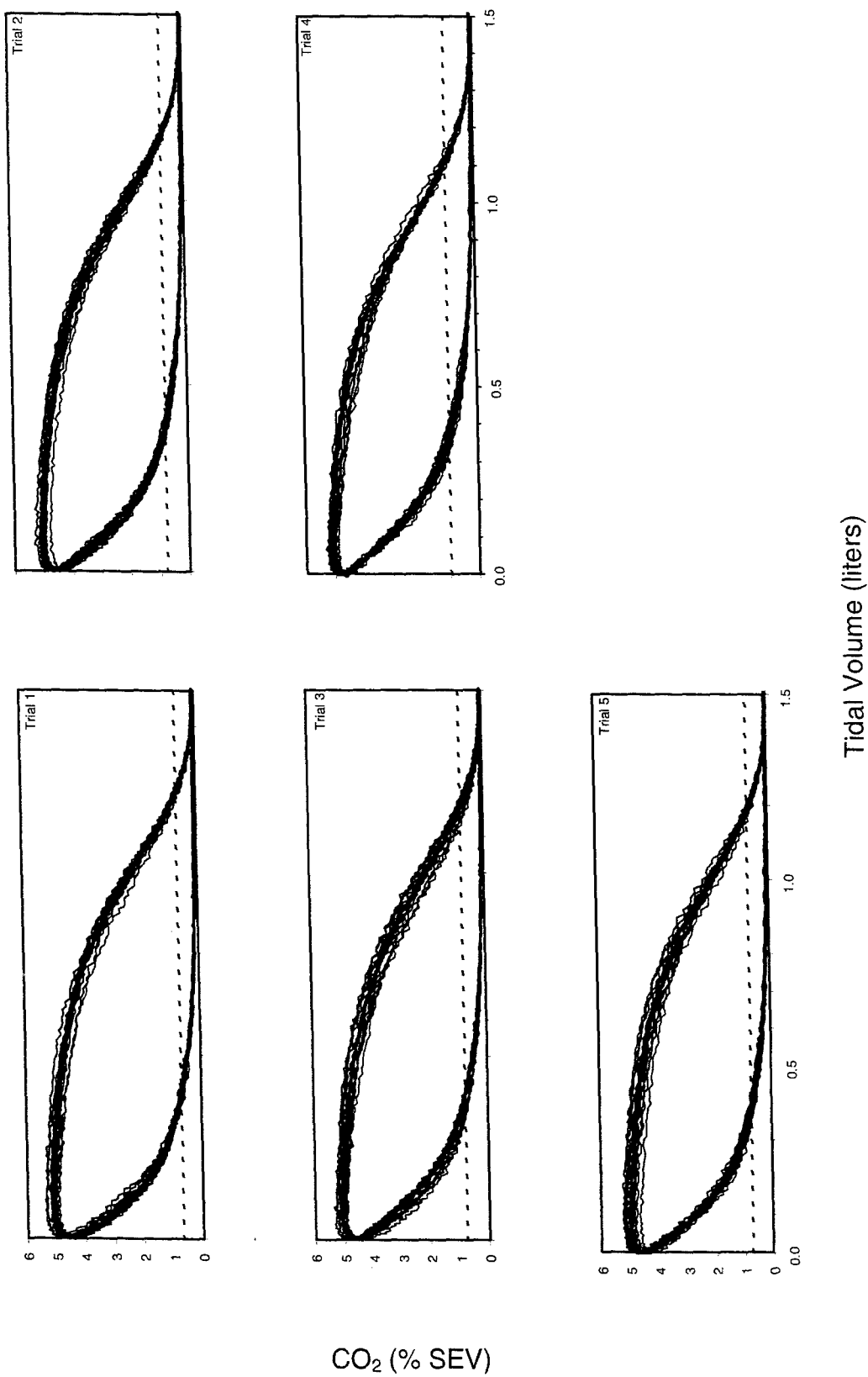


Figure 7. Normalized volume-averaged inspired CO₂ of the modified EBS mask when the slots in the inhalation hose are near the mask and those in the exhalation hose are positioned away from the mask. The dotted line in each panel indicates the average inspired level of CO₂.