# Evaluation of a Rebreathing System for Use with Portable Mechanical Ventilators

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## ABSTRACT

**Introduction:** Maximizing the capabilities of available low-flow oxygen is key to providing adequate oxygen to prevent/treat hypoxemia and conserve oxygen. We designed a closed-circuit system that allows rebreathing of gases while scrubbing carbon dioxide ($CO_2$) in conjunction with portable mechanical ventilators in a bench model. **Methods:** We evaluated the system using two portable mechanical ventilators currently deployed by the Department of Defense—Zoll 731 and AutoMedx SAVe II—over a range of ventilator settings and lung models, using 1 and 3L/min low-flow oxygen into a reservoir bag. We measured peak inspired oxygen concentration ($FiO_2$), $CO_2$-absorbent life, gas temperature and humidity, and the effect of airway suctioning and ventilator disconnection on $FiO_2$ on ground and at altitude. **Results:** $FiO_2$ was ≥0.9 across all ventilator settings and altitudes using both oxygen flows. $CO_2$-absorbent life was >7 hours. Airway humidity range was 87%–97%. Mean airway temperature was 25.4°C (SD 0.5°C). Ten-second suctioning reduced $FiO_2$ 22%–48%. Thirty-second ventilator disconnect reduced $FiO_2$ 29%–63% depending on oxygen flow used. **Conclusion:** Use of a rebreathing system with mechanical ventilation has the potential for oxygen conservation but requires diligent monitoring of inspired $FiO_2$ and $CO_2$ to avoid negative consequences.

KEYWORDS: *mechanical ventilation; oxygen; rebreathing; hypoxemia; transport*

## Introduction

Under normal hospital conditions, oxygen is abundant. Under far forward conditions and in resource-poor areas, oxygen may be scarce.[1–4] Supplying oxygen in austere/resource-constrained environments presents significant logistical challenges. In military applications, oxygen is a finite resource, and methods for conservation include targeted oxygen delivery, closed-loop control of inspired oxygen, and use of chemical oxygen generators and oxygen concentrators.[5,6] In situations where the use of pressurized oxygen cylinders is logistically difficult or not permitted due to potential hazards including fire and projectile risks, low-flow oxygen from alternative sources is the next available option. Maximizing the capabilities of low-flow oxygen is key to providing adequate oxygen to prevent/treat hypoxemia and conserve oxygen.

Anesthesia workstations have been used in the operating room for decades and are well understood. These workstations cost over $150,000 and typically do not have advanced ventilator modes and monitoring. These devices use a circle system that allows rebreathing of the patient's exhaled gases while eliminating exhaled carbon dioxide ($CO_2$) via a $CO_2$ absorbent while recirculating anesthetic gases and oxygen. The $CO_2$ absorbent used is typically composed of soda lime and small amounts of other chemicals that remove $CO_2$ by chemically converting it to calcium carbonate. Heat and water are the byproducts of these reactions. The absorbent granules change color when saturated with $CO_2$, providing a visual indicator that the absorbent's ability to capture $CO_2$ has reached its capacity.[7]

Many early rebreathing system configurations are attributed to designs by Mapelson.[8,9] These systems were simple to operate but were inefficient and required fresh gas flows of 1–3 times the patient's minute ventilation in order to prevent rebreathing of $CO_2$. Modifications of these early systems to mitigate the dangers $CO_2$ rebreathing and excessive fresh gas use led to the advent of circle or closed systems.[10] This innovation allowed for much lower fresh gas flows while producing a higher $FiO_2$. In anesthesia, lower fresh gas flows allow conservation of expensive anesthetic agents. We designed a closed-circuit system that allows rebreathing of gases while scrubbing $CO_2$ in conjunction with mechanical ventilation in a bench model.

## Methods

We used two portable mechanical ventilators currently employed by the Department of Defense (DoD)—the 731 (Zoll Medical, Chelmsford, MA) and SAVe II (AutoMedx, Addison, TX)—for the evaluation. The experiment's design is shown in Figure 1. Figure 2 shows the rebreathing system as it would be connected to a patient. We evaluated the system over a range of ventilator settings that represent the likely range of respiratory rates (RRs) and tidal volume ($V_T$) required by most patients (Table 1) and two lung conditions representing normal lung compliance and low lung compliance that may be required for patients with acute respiratory distress syndrome (ARDS) (Table 2). An engineering group (Sparx Engineering, Manvel, TX) designed and 3D printed the $CO_2$ absorber canister incorporated into the rebreather system. A soda lime–based 3L absorbent (Sodasorb, Molecular Products Inc., Louisville, CO) was used for the evaluation. The canister was placed in the inspiratory limb. We introduced oxygen flows of 1 and 3L/min into a 3L reservoir bag attached to the ventilator inlet and made the following measurements:

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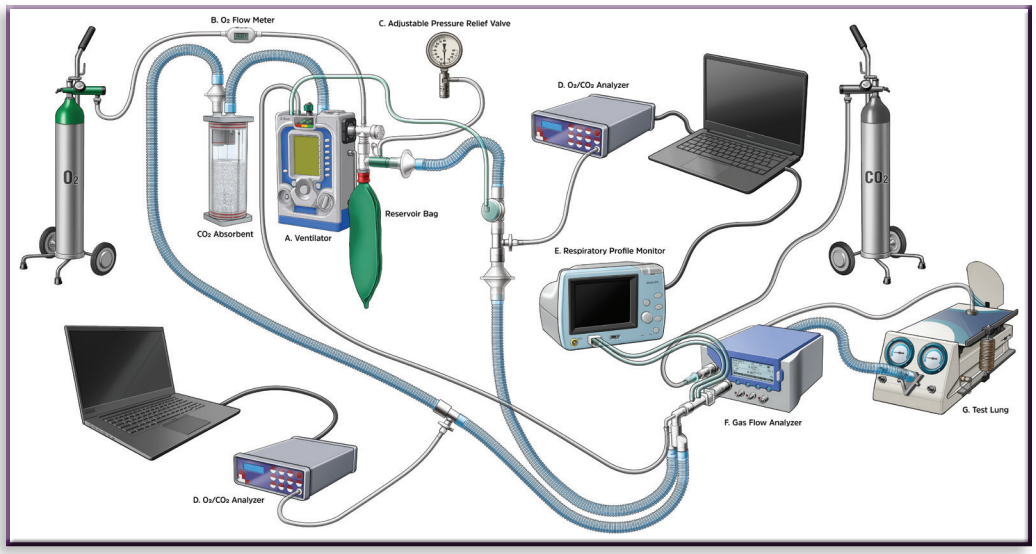


**FIGURE 1** *Experiment setup.*

- peak inspired oxygen concentration ($FiO_2$) within 30 minutes;
- duration of $CO_2$-absorbent life (determined by a rise in inspired $CO_2$ >1%);
- peak delivered gas temperature and humidity;
- volume of condensate produced in the ventilator circuit;
- effect of 5- and 10-second airway suctioning with in-line suction catheter on $FiO_2$; and
- effect of 15- and 30-second ventilator circuit disconnect on $FiO_2$.

**FIGURE 2** *Rebreather system connected to a patient.*

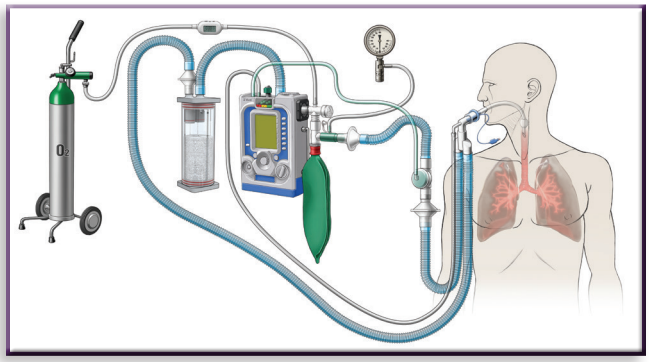


**TABLE 1** *Ventilator Settings For the Evaluation*

| Ventilator | RR combinations, (breaths/min)/$V_T$, mL | PEEP, cm $H_2O$ | I:E | Breath type |
|---|---|---|---|---|
| SAVe II | 30/250<br>18/450<br>11/700 | 5 | 1:2 | Volume |
| 731 | 30/250<br>20/450<br>20/700 | 5 & 20 | 1:3 | Volume |

RR = respiratory rate; I:E = inspiratory:expiratory; PEEP = positive end expiratory pressure.

**TABLE 2** *Test Lung Settings For the Evaluation*

| | Compliance, mL/cm $H_2O$ | Resistance, cm $H_2O$/L/s | $CO_2$ production, mL/min |
|---|---|---|---|
| Normal | 80 | 5 | 200 |
| ARDS | 20 | 10 | 200 |

ARDS = acute respiratory distress syndrome.

Ventilators were attached to a test lung (TTL, Michigan Instruments, Kentwood, MI) which allows for setting a range of lung compliance. Peak $FiO_2$ was measured (Oxigraf, Sunnyvale, CA) in the ventilator circuit inspiratory limb near the patient connector with both ventilators and all combinations of ventilator settings. Remaining measurements were only made with the 731 using the RR20/$V_T$ 450/positive end expiratory pressure (PEEP) 5 settings (plus RR30/$V_T$ 250/PEEP5 and RR20/$V_T$ 700/PEEP5 for the duration of $CO_2$-absorbent life tests). Testing was done in duplicate at ground level, 8,000-ft, and 16,000-ft simulated altitude in a non–human-rated altitude chamber (Abyss Instruments, Holliston MA) with the exception the absorbent life test, which was completed 5 times at ground level. The same altitude chamber was used for all altitude testing. Nitrogen gas was introduced into the test lung during the $FiO_2$ testing as needed to maintain a 2%–3% lower expired than inspired $FiO_2$ to simulate normal oxygen consumption. $CO_2$ was introduced into the test lung from a cylinder at 200mL/min to simulate $CO_2$ production.

Airway suctioning was simulated by placing a closed suction system (Ballard, Avanos Medical, Inc., Alpharetta, GA) at the patient connector and activating continuous suction for 5 and 10 seconds. The lowest $FiO_2$ was measured after the designated suction time. The $FiO_2$ recovery time was measured from end of suctioning maneuver until initial $FiO_2$ was reached. No suctioning material was used for this maneuver.

### *Statistical Analysis*

Stratified by device, one-way ANOVA was used to model $FiO_2$ as a function of ventilator settings and altitude, while unpaired *t* tests were used to model the effect of oxygen flow (1 vs. 3L/min); the *p*-value for significance was set at .05.

Five trials were performed for each of three sets of ventilator settings (RR 30/$V_T$ 250mL, RR 20/$V_T$ 450mL, RR 20/$V_T$ 700mL, all with PEEP of 5cm $H_2O$ and lung compliance of 80mL/cm $H_2O$ and 1L/min oxygen flow rate) for the $CO_2$-absorbent life testing. Between-settings differences in temperature, humidity, and minutes to inspired $CO_2$ >1% were assessed using one-way ANOVA. Pairwise comparisons were done using a *t* test. Statistical significance was set at $p<.05$.

## Results

### $FiO_2$

$FiO_2$ during use of the 731 was not impacted by ventilator settings ($p$>.99). Mean $FiO_2$ was 0.96 (SD 0.25) for all settings. $FiO_2$ was significantly ($p$=.04) associated with altitude and tended to be lower at higher altitudes although differences were not clinically important. Mean $FiO_2$ was 0.97 (SD 0.02) at ground level, 0.96 (SD 0.02) at 8,000 feet, and 0.95 (SD 0.03) at 16,000 feet (Figure 3). $FiO_2$ was significantly ($p$<.001) higher with 3L/min oxygen bleed-in, versus 1L/min. Mean $FiO_2$ was 0.94 (SD 0.02) with 1L/min oxygen bleed-in and 0.98 (SD 0.01) with 3L/min oxygen bleed-in (Figure 4). Minimum $FiO_2$ in each group was 0.92 and 0.97, respectively.

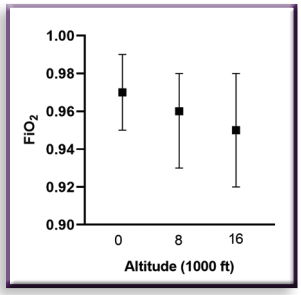


**FIGURE 3** *Effect of Altitude on Fio2 (mean and range) showing combined 1 and 3L/min oxygen flows at each altitude with the 731 ventilator.*

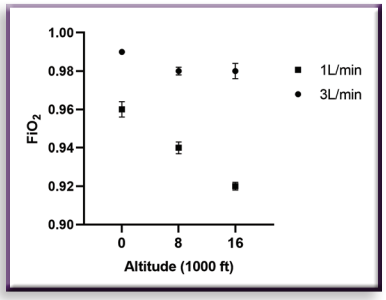


**FIGURE 4** *Effect of oxygen flow on $FiO_2$ (mean and range) with the 731 ventilator.*

$FiO_2$ during use of the SAVe II was not associated with ventilator settings ($p$=.73) or altitude ($p$=.97). It should be noted that the maximum PEEP setting with the SAVe II was 10cm $H_2O$,[11] therefore the ventilator settings requiring 20cm $H_2O$ PEEP were not possible. There was a minimal decrease in mean $FiO_2$ with increasing altitude: 0.95 (SD 0.03) at ground level, 0.94 (SD 0.26) at 8,000 feet, and 0.94 (SD 0.27) at 16,000 feet. $FiO_2$ was significantly ($p$<.0001) higher with 3L/min oxygen, versus 1L/min and was less variable (Figure 5). Mean $FiO_2$ was 0.92 (SD 0.01) at 1L/min oxygen, and 0.97 (SD 0.01) at 3L/min (mean difference 0.05). Minimum $FiO_2$ in each group was 0.9 and 0.96, respectively. Due to the limited flow limitations (24L/min)[11] and PEEP limitations of the SAVe II, direct $FiO_2$ comparisons to the 731 could only be made using the $RR30/V_T$ 250/PEEP 5 settings. Differences in $FiO_2$ between the two devices at these settings were not significantly different ($p$=.97).

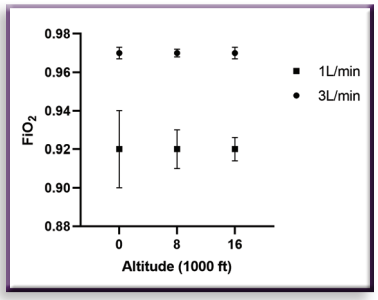


**FIGURE 5** *Effect of oxygen flow on Fio2 (mean and range) with the SAVe II ventilator.*

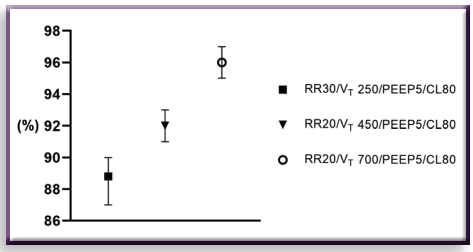


**FIGURE 6** *Effect of ventilator settings on humidity (mean and range).*

## Temperature and Humidity

Mean humidity was 89% (range 87%–90%) for $RR30/V_T$ 250 settings, 92% (91%–93%) for $RR20/V_T$ 450, and 96% (95%–97%) for $RR20/V_T$ 700 (Figure 6). Differences were statistically significant overall ($p$<.0001) as were all pairwise comparisons. Peak temperature did not differ significantly between the three $RR/V_T$ ventilator settings ($p$=.47). Group means were 25.5°C, 25.2°C, and 25.6°C, respectively.

### $CO_2$ Absorbent Life

Mean time to $CO_2$ elevation of >1% was 456 (SD 56) mins for $RR30/V_T$ 250, 460 (SD 44) mins for $RR20/V_T$ 450, and 557 (SD 27) mins for $RR20/V_T$ 700 ventilator settings (Figure 7). This difference was statistically significant overall ($p$=.005) but not all pairs were significantly different: $RR20/V_T$ 700 was significantly different from the other ventilator settings (both $p$<.01), but the $RR30/V_T$ 250 and $RR20/V_T$ 450 settings were not significantly different from each other ($p$=.89.)

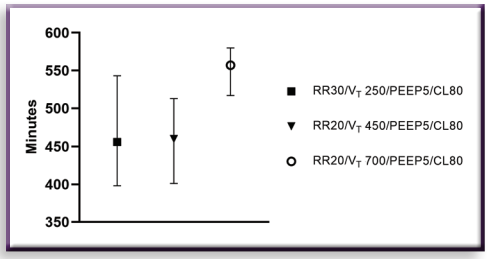


**FIGURE 7** *Effect of ventilator settings on time to $CO_2$ >1% (mean and range).*

Condensate from the ventilator circuit was drained and measured after each test (data not shown). The longest the run times produced the largest condensate volume. The condensate volume produced by the $RR30/V_T$ 250 and $RR20/V_T$ 450 ventilator settings run times were not significantly different ($p$=.55, range 25–35mL) whereas these settings produced condensate volumes that were significantly different from volumes produced using the $RR20/V_T$ 700 ventilator settings (range 45–63mL, $p$=.005 and $p$=.0003, respectively).

### Suctioning and Disconnect

$FiO_2$ at baseline, after 5 and 10 seconds of airway suctioning, and after 15 and 30 seconds of a ventilator disconnect, and recovery times back to baseline $FiO_2$ are shown in Table 3. With the exception of the 15-second ventilator circuit disconnect and the 5-second suction recovery time, the 1L/min $O_2$ bleed-in tests resulted in significantly greater decreases in $FiO_2$ and significantly longer recovery time than the 3L/min tests and at baseline ($p$<.05). The 15-second ventilator circuit disconnect did not result in significantly different $FiO_2$ with either the 1 or 3L/min $O_2$ tests ($p$>.1). Within-group (1 and 3L/min) $FiO_2$ and recovery time was significantly different ($p$<.05) with the exception of the 15-second ventilator circuit disconnect ($p$>.1).

**TABLE 3** *$FiO_2$ and Recovery Time After 5- and 10-Second Suctioning and 15- and 30-Second Ventilator Circuit Disconnect Using 1 and 3L/min Oxygen*

| | $O_2$ test, mean (SD) | |
|---|---|---|
| | 1L/min | 3L/min |
| Baseline $FiO_2$ | 0.96 (0.003) | 0.99 (0.01) |
| 5-second suction $FiO_2$ | 0.9 (0.01) | 0.93 (0.001) |
| Recovery time, s | 5.3 (0.4) | 4.0 (1.4) |
| 10-second suction $FiO_2$ | 0.47 (0.09) | 0.77 (0.04) |
| Recovery time, s | 1125.5 (140.7) | 334.5 (14.8) |
| 15-second disconnect $FiO_2$ | 0.96 (0.001) | 0.99 (0.01) |
| Recovery time, s | 0 | 0 |
| 30-second disconnect $FiO_2$ | 0.32 (0.05) | 0.69 (0.02) |
| Recovery time, s | 1446 (178) | 443 (5.7) |

## Discussion

This study showed that a rebreathing system can be adapted to selected portable ventilators and provides $FiO_2$ ≥90% with 1–3L/min oxygen introduced into the system over a range of ventilator settings and lung conditions, while scrubbing $CO_2$ from the inspired gas. The study also showed the effects of airway suctioning and ventilator disconnect on delivered $FiO_2$ as well as the volume of condensate produced and capacity of the $CO_2$ absorbent.

Full-size rebreathing anesthesia machines are too cumbersome and weight- and cube-prohibitive for use in transport and/or austere environments. Oswald and DeBoer in the early 1990s described a closed-circuit anesthesia device developed for transport use with off the shelf components.[12] The potent agent portable apparatus (PAPA) was intended to be used for anesthesia gas delivery but could also be used without anesthesia, potentially extending the life of an oxygen cylinder. The device was much smaller and lighter (30lbs) than a typical anesthesia machine and could be mounted to a hospital bed, but it required fresh gas flows up to 6L/min, albeit an improvement over its predecessors. Pollock and Natoli conducted a pilot study with 6 normal subjects, evaluating the performance of a closed-circuit emergency medical oxygen (REMO(2)) system designed for field use in a laboratory setting. Subjects breathed spontaneously on the device via oronasal mask for 8 hours. The device provided 0.93–0.98 peak $FiO_2$ using 1.0 (SD 0.17) L/min oxygen flow. However, this device did not provide positive pressure ventilation, instead relying on users to generate their own minute ventilation.[13]

In the hospital setting, oxygen is generally abundant and inexpensive, but this is often not the case in combat and aeromedical evacuation settings. Oxygen containing and/or generating equipment occupy 15%–30% of the available footprint for a given setting[14,15] and represent substantial weight.[14] Because of these logistical constraints, efforts have been made to reduce oxygen usage primarily by the automatic titration of oxygen delivery to a target oxygen saturation ($SpO_2$).[14–16] Barnes et al. found in an observational study that 68% of mechanically ventilated aeromedical transport combat casualties required <3L/min oxygen.[17] Although this was a small observational study with important findings, a substantial number of casualties required higher $FiO_2$, prompting a search for a potential solution to providing higher $FiO_2$ while using ≤3L/min oxygen, the maximum flow provided by portable oxygen concentrators deployed by the DoD (Saros, Caire Inc, Ball Ground, GA).

Lowes and Sharley evaluated the Modified Circle System (MCS), an adaptation of the closed-circuit anesthesia system, in a bench model.[6] The evaluation used two $V_T$/RR combinations, two PEEP settings, and normal and stiff lung settings. The majority of the testing was accomplished with an LP10 ventilator (Puritan Bennett, Medtronic, Minneapolis, MN). Across all settings, the authors found that the oxygen flow required to maintain a stable $FiO_2$ >0.93 was 0.75–1.5L/min. The findings were similar to the results of a portion of our study, although the goal of our testing was to determine the highest $FiO_2$ using two oxygen flows over a range of ventilator/lung compliance settings and three altitudes. The setup configurations were similar with the MCS and our system with two exceptions. The $CO_2$ absorber in the MCS model was placed on the ventilator air intake side versus the ventilator output side with our configuration. Additionally, the LP10 has an external PEEP valve versus the PEEP being controlled internally with the ventilators we used for testing. We initially attempted to place the $CO_2$ absorber on the ventilator air intake, but this configuration interfered with ventilator PEEP controls and resulted in alarms, necessitating placement of the $CO_2$ absorber in the inspiratory limb. Placement in the inspiratory limb where the ventilator provides the power to overcome the resistance is also an advantage. Using the external PEEP valve likely allowed for the $CO_2$ absorber attachment to the LP10 without an impact on PEEP.

Duration of mechanically ventilated patient transports can vary widely depending on the transportation method. Ground and rotor wing transports are relatively short in duration. Buchanan et al. reported that transport time for trauma patients to the referring hospital from the scene via ground or rotor wing transport was <30 minutes.[18] Transport time would obviously depend on the distance from the referring facility. Aeromedical fixed wing transports can range from 30 minutes to 16 hours.[18] Duration of transcontinental aeromedical transports from Iraq and Afghanistan to Germany were approximately 7 hours.[19–20] The rebreather system $CO_2$-absorbent life in our study was 7.6 hours (SD 56 minutes) which would satisfy the requirement for operation for most of these transports. For longer transports and prolonged field care, the absorbent must be replaced or another full absorbent canister available to replace the canister and exhausted absorbent.

One of the most important aspects when discussing these closed-circuit systems is the effect of breaking the system, potentially resulting in decreased $FiO_2$ and patient hypoxia. Mechanically ventilated patients often require suctioning via in-line suction catheters or disconnection from the ventilator for open suctioning. Our study showed that utilizing in-line suction for 10 seconds or disconnection from the ventilator for 30 seconds can result in low $FiO_2$ and recovery times back to baseline from 5 to 24 minutes, depending on oxygen flow used. These results suggest that with patients requiring high $FiO_2$ to maintain oxygenation airway suctioning and ventilator circuit, disconnection should be limited because of the risks of hypoxemia and resulting sequelae.

### *Limitations*

There are a number of limitations with this study. This was a bench study conducted under controlled settings including room temperature, close control of $CO_2$ production, oxygen delivery and simulated oxygen consumption. We cannot be certain the rebreathing system would perform the same if used with patients

with differing $CO_2$ production and/or oxygen consumption, with and without spontaneous breathing. We only studied two portable ventilators and only one of each model. The system may perform differently with other ventilators. The rebreather system was studied at simulated altitudes in an altitude chamber. The system may perform differently in real-world conditions at altitudes encountered during aeromedical transport.

We did not evaluate long-term use on ventilator function (moisture in the ventilator inlet) nor did we evaluate the potential for contamination of the ventilator and need for cleaning between patients. Although we used several filters within the system, perhaps these should be HEPA filters to reduce bacterial/viral contamination. The T1 portable ventilator (Hamilton Medical, Bonaduz, Switzerland) is used in selected DoD medical scenarios and was considered for evaluation in this study. At the time of this study, our T1 ventilator did not have an inlet that allowed attachment to the rebreathing system via standard connectors to collect the expired gas and therefore could not be adapted to the system for evaluation.

Unlike standard oxygen supplementation, rebreathing carries an additional risk. Under standard operation, exhaustion of oxygen supplies or accidental disconnection results in delivery of room air. Loss of the oxygen supply in a rebreathing system can result in delivery of hypoxic gas mixtures and patient injury.

## Conclusion

The results of this study show that using low oxygen flow ≤3L/min with a rebreathing system attached to a portable ventilator can provide $FiO_2$ ≥90% across a range of ventilator settings and lung models, both at ground level and at altitude. In its current form, this system is not compatible with some portable ventilators owing to its inability to attach to the ventilator air intake in order to complete the closed system. Suctioning and disconnection from the ventilator should be used sparingly because of the risk of hypoxemia. In our models, $CO_2$-absorbent life was at least 7 hours at all conditions, which would be adequate for most aeromedical and ground transports and anywhere oxygen is scarce. Use of a rebreathing system has the potential for oxygen conservation but requires diligent monitoring of inspired $FiO_2$ and $CO_2$ to avoid negative consequences. The addition of an oxygen analyzer and capnograph to assure safety adds cost, complexity, and logistical hurdles.

### Author Contributions

TB and RB conceived the concept. TB conducted the experiment, collected and compiled the data, and wrote the first draft. MS provided the statistics, TB, RB, and MS conducted data analysis. All authors read and approved the final manuscript.

### Disclosures

The authors do not have financial relationships relative to this article to disclose.

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### Disclaimer

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