AFRL-RH-WP-TR-2021-0053

Maximizing Oxygen Delivery Across Deployed Services

Thomas Blakeman
University of Cincinnati

Dario Rodriquez
711 HPW/RHBA

John Fowler
Cape Fox Federal Integrators

SEPTEMBER 2021
Final Report

Distribution Statement A: Approved for public release.

See additional restrictions described on inside pages

AIR FORCE RESEARCH LABORATORY
711TH HUMAN PERFORMANCE WING,
AIRMAN SYSTEMS DIRECTORATE,
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RH-WP-TR-2021-0053 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//SIGNATURE//	//SIGNATURE//
JAMES B. LEHMAN	DARIO RODRIQUEZ, JR, DR-III, DAF
Research Program Manager	En Route Care Product Area Lead
Product Development Branch	Product Development Branch
Airman Biosciences Division	Airman Biosciences Division

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)* 20-02-21

2. REPORT TYPE Final

3. DATES COVERED *(From - To)* September 2017 – August 2021

4. TITLE AND SUBTITLE
Maximizing Oxygen Delivery Across Deployed Devices

5a. CONTRACT NUMBER FA8650-15-2-6605

5b. GRANT NUMBER FA8650-17-2-6G28

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
* Thomas Blakeman
** Dario Rodriquez
*** John Fowler

5d. PROJECT NUMBER 18-003

5e. TASK NUMBER 28G

5f. WORK UNIT NUMBER Legacy RHM

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
*University of Cincinnati
Sponsored Research Services
51 Goodman Drive, Suite 530
Cincinnati, OH 45221-0222

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
**Air Force Materiel Command
Air Force Research Laboratory
711th Human Performance Wing
Airman Systems Directorate
Airman Biosciences Division
Product Development Branch
Wright-Patterson AFB, OH 45433

*** Cape Fox Federal Integrators

10. SPONSORING/MONITORING AGENCY ACRONYM(S) 711 HPW/RHBA

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RH-WP-TR-2021-0053

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release.

13. SUPPLEMENTARY NOTES
AFRL-2021-3272, cleared 27 September 2021

14. ABSTRACT Background: Maintaining oxygen (O_2) supplies for mechanically ventilated military transport patients is crucial. A portable oxygen concentrator (POC) can provide an endless supply of O_2. Evidence suggests that 3 L/min of O_2 could manage 2/3 of the mechanically ventilated military aeromedical transport patients. Methods: We evaluated two each of the AutoMedx SAVe II, Hamilton T1, Zoll 731, and Ventec VOCSN portable ventilators paired with 1 and 2 Caire SAROS POCs at ground level and simulated altitudes. Ventilator parameters and FiO_2 were continuously measured. Each ventilator was attached to a test lung. POC output was bled-in to each ventilator via the mechanism provided with each device. Results: FiO_2 varied between ventilator models. Differences in FiO_2 between ventilators at a majority (98.5%) of testing conditions was statistically significant ($p < 0.05$) but not all were clinically important. The Zoll 731 delivered the highest and most consistent FiO_2 over all ventilator/POC settings and altitudes. Differences in FiO_2 at a given ventilator/POC setting from ground level through 22,000 ft were not clinically important (<5%) with this device. Conclusions: Oxygen delivery utilizing POCs is dependent upon multiple factors including ventilator operating characteristics, ventilator settings, altitude, and the use of pulsed dose or continuous flow O_2.

15. SUBJECT TERMS
oxygen delivery, portable oxygen concentrators, mechanical ventilation, transport, aeromedical evacuation, altitude

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
U	U	U	SAR	16	James Lehman **19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

TABLE OF CONTENTS

1.0 BACKGROUND

Transportation of the critically ill or injured war fighter requires the coordinated care and judicious use of resources. Availability of oxygen (O_2) supplies for the mechanically ventilated patient is crucial. Size and weight of cylinders makes transport difficult and presents an increased risk of fire. A proposed solution is to use a portable oxygen concentrator (POC) to supply oxygen for mechanical ventilation. A POC would allow for continuous output of O_2, provided power is available. Previous efforts have identified that as little as 3 Liters/minute) (L/min) of O_2 could manage as much as 68 percent (%) of U.S. Air Force Critical Care Air Transport Team (CCATT) patients[1]. Current missions have moved to a battlespace that has limited resources and the implementation of POCs has proven beneficial with the use of a single device. Combining multiple POCs has not been described in the literature under those environmental conditions. The intent of this study was to determine the capability of multiple POCs to support mechanical ventilation in austere environments and evaluate the potential benefit of possibly reducing the reliance on compressed/liquid O_2, while maintaining the same standard of care. This study was reviewed by the University of Cincinnati Institutional Review Board and the Air Force Research Laboratory, Human Resources Protection Office and was classified as a Non-Human Use research activity.

2.0 METHODS

We evaluated 2 each of 3 ventilator models currently deployed for field use by the Department of Defense (DoD): Zoll 731 (Zoll Medical, Chelmsford, MA), Hamilton T1 (Hamilton Medical, Reno, NV), SAVe II, AutoMedx LLC, Addison, TX), and 2 of a newly developed portable ventilators (VOCSN, Ventec Life Systems, Bothell, WA). The VOCSN offers 4 adult circuit configurations: Active, passive, valveless, and mouthpiece circuits. We use the active circuit with integrated O_2 tube for the evaluation. Each ventilator was paired with 1 and 2 POCs (Model 3000, Sequal SAROS, Caire Inc, Ball Ground, GA) also currently deployed by the Department of Defense, at ground level and simulated altitudes of 8,000 feet (ft), 16,000 ft, and 22,000 ft in a man-rated altitude chamber (Wright Patterson AFB, OH). See table 1 for testing conditions.

Table 1. Testing matrix used for the evaluation

Respiratory Rate	Tidal Volume (mL)	Inspiratory Time (sec)	PEEP (cm H_2O)	Lung Compliance (cmH2O/L/sec)
30	250	0.5	5	80
30	250	0.5	20	20
20	450	0.75	5	80
20	450	0.75	20	20
20	700	0.75	5	80
20	700	0.75	20	20

Table 1. Testing matrix used for the evaluation. Each condition was tested using both 1 and 2 POCs or pulsed dose equivalent (VOCSN using internal concentrator).

Testing was done twice with each ventilator at each testing condition. The maximum continuous flow output of each POC is 3 L/min producing a reported Free Inspired Oxygen (FiO_2) of 93 ± 3%[2]. This flow rate was used for all tests. The Ventec VOCSN has the capability of utilizing an internal O_2 concentrator that employs pulsed dose technology, which was also evaluated. Output from the POC(s) was bled-in to each ventilator via the mechanism provided with each device. The 731 was kitted with a 3-liter reservoir bag that attaches to the ventilator air intake port which allows mixing of bled-in oxygen with entrained room air. Similarly, the SAVe II utilizes an expandable large bore tubing on the air intake port containing an adapter that also allows mixing of bled-in oxygen with entrained room air. The remaining ventilators provided a connection for simple oxygen tubing directly into the device. High pressure gas supply was not necessary for ventilator operation as each was powered by either an internal compressor or blower. Each ventilator was attached to a single chamber Training Test Lung (TTL), (Michigan Instruments, Grand Rapids, MI). A Fleisch pneumotach model 4700 with data acquisition via SmartLab Data Acquisition system (Hans Rudolph, Shawnee, KS) was placed between the ventilator circuit and the TTL to measure delivered ventilator parameters. A fast response O_2 analyzer (O2CAP, Oxigraf Inc, Sunnyvale, CA) was placed in the provided port on the TTL to measure FiO_2 within the simulated lung. Appropriate dead space to simulate the airway anatomy of a 68-kilogram (kg) man was added between the ventilator circuit and TTL for pulsed dose O_2 delivery with the VOCSN. Each ventilator/concentrator combination was allowed to stabilize for 1-2 minutes or until FiO_2 was stable at each setting. Breath to breath ventilator output and FiO_2 were continuously measured and recorded at ground level and each altitude for later analysis.

3.0 STATISTICAL ANALYSIS

The comparisons of FiO_2 were analyzed utilizing the one-way analysis of variance (ANOVA), with a significance level of 0.05. Each combination of tidal volume (V_T) (250, 450, and 700 milliliters (mL), lung compliance (C_L) (20 and 80 mL/centimeter of water (cm H_2O) and POC (1 and 2) compared altitude groups (Sea level, 8000, 16,000 and 22,000 ft) for each device combination. Positive End Expiratory Pressure (PEEP) settings (5 & 20 cm H_2O) and POC combinations compared each altitude level separately and each ventilator was compared by altitude combinations. All comparisons were adjusted by Tukey–Kramer multiple comparison tests for post hoc analysis. All analyses were conducted using SAS 9.4 (SAS Institute, Cary, NC)

4.0. RESULTS

Delivered FiO_2 varied between ventilators when paired with both 1 & 2 POCs and among the same ventilator model at various altitudes. A total of 522 comparisons were completed and 514 (98.5%) were highly statistically significant ($p \leq 0.01$), although many of those can be attributed to a large number of samples and low standard deviations. The 731 consistently delivered the highest FiO_2 at all ventilator/POC combinations at ground level and all altitudes. Figures 1-3 show the delivered FiO_2 at each V_T setting respectively with 1 & 2 POCs, PEEP of 5 & 20 cm H_2O at ground level and all altitudes. The SAVe II paired with 1 POC delivered FiO_2 comparable to the 731 at the 250 mL setting using 5 cm H_2O PEEP, but FiO_2 was considerably lower than the 731 with the 250 mL V_T/2 POC setting. Due to the limited performance capabilities, this device was unable to perform the remainder of the testing protocol. The T1 failed to operate appropriately at 16,000 and 22,00 ft altitude at selected settings due to delivered V_Ts > 10% of set V_T or error messages “Pressure limitation” and/or “Performance limited by high altitude” which resulted in V_T alterations. One VOCSN ventilator’s internal concentrator failed at 22,000 ft therefore FiO_2 with that ventilator model at that altitude was analyzed with data from 1 device. The VOCSN using the integrated internal concentrator delivered the lowest FiO_2 in 34 of 48 (71%) ventilator/POC/altitude settings.

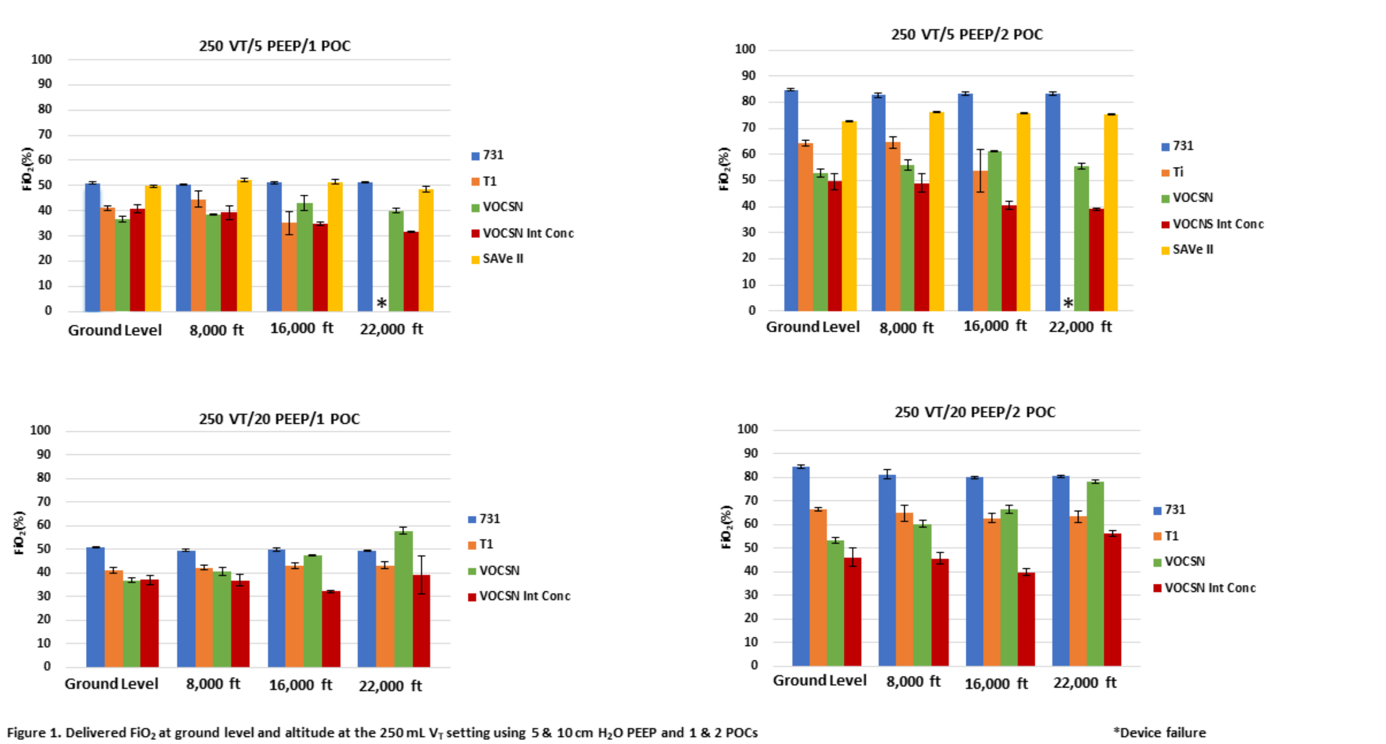

Figure 1. Delivered FiO_2 at ground level and altitude at the 250 mL V_r setting using 5 & 10 cm H_2O PEEP and 1 & 2 POCs

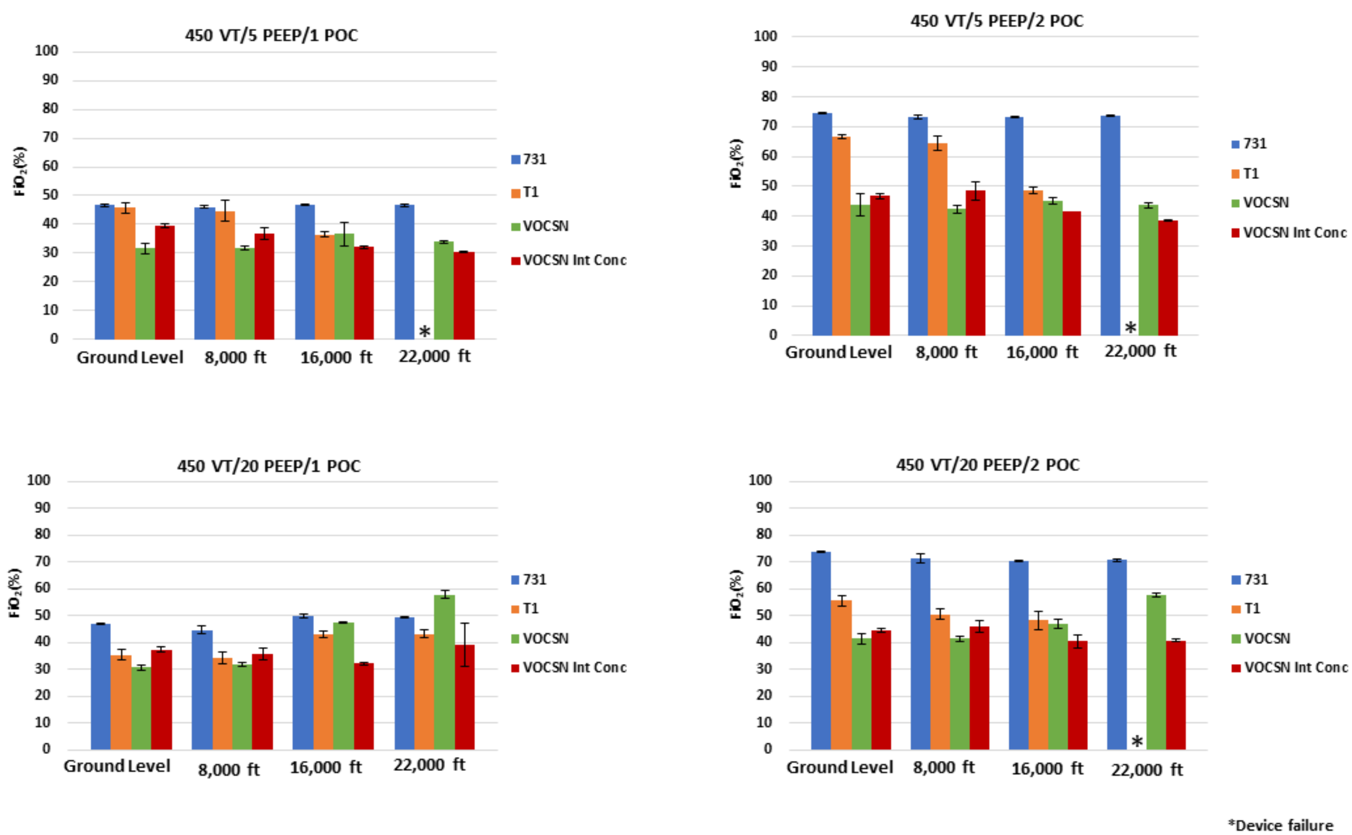

Figure 2. Delivered FiO_2 at ground level and altitude at the 450 mL V_T setting using 5 & 10 cm H_2O PEEP and 1 & 2 POCs

Figure 2. Delivered FiO_2 at ground level and altitude at the 450 mL V_r setting using 5 & 10 cm H_2O PEEP and 1 & 2 POCs

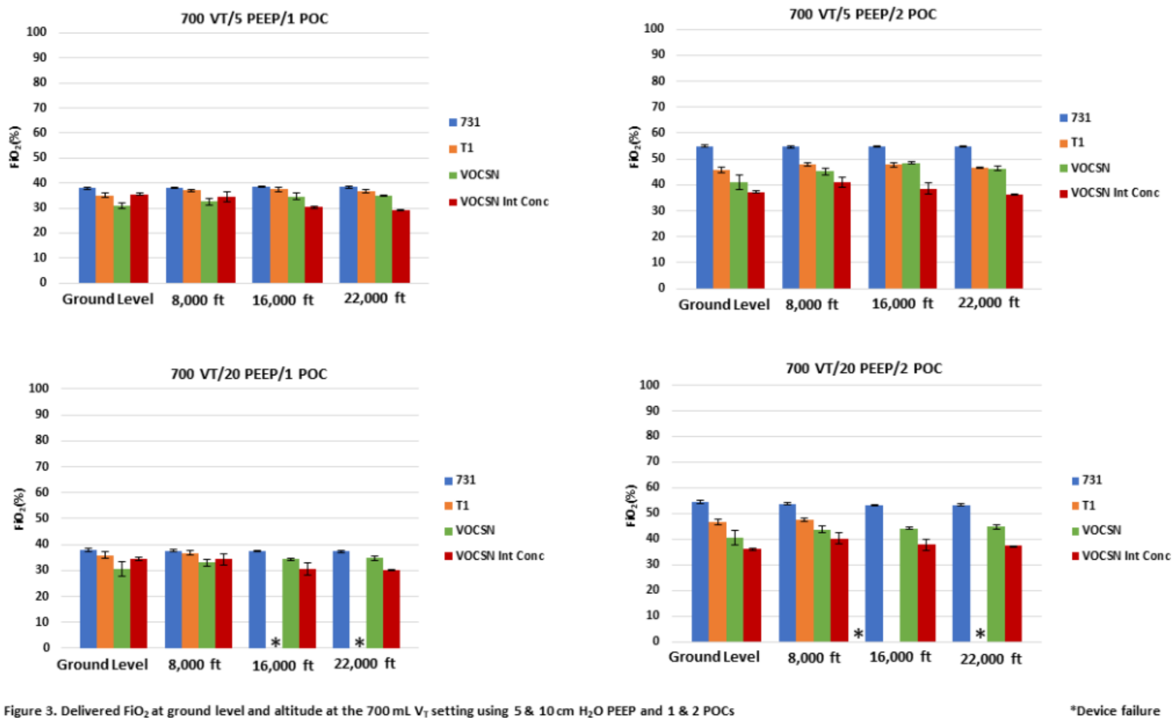

Figure 3. Delivered FiO_2 at ground level and altitude at the 700 mL V_r setting using 5 & 10 cm H_2O PEEP and 1 & 2 POCs

5.0 DISCUSSION

The results of this study showed that the FiO_2 delivered when utilizing POCs to provide O_2 during mechanical ventilation varies widely depending on the ventilator and the altitude at which the devices are used. A search of the literature revealed several bench studies evaluating POCs alone at ground level[3,4] at altitude,[5-9] and paired with portable ventilators at ground level.[10-16] To our knowledge there was only 1 bench study similar to ours pairing 1 & 2 POCs (SAROS) with a single compressor-driven portable ventilator performed at altitudes of 1,200 and 6,500 ft. The results of the study showed that the POC(s) could deliver an FiO_2 of 90% provided the minute ventilation did not exceed the liter flow of the POC. Additionally, the delivered FiO_2 was slightly higher at 1,200 ft altitude as compared to 6,500 ft and the difference increased with increased minute ventilation.[17] These findings are in contrast to our prior work with POCs at altitude suggesting that mean FiO_2 increased with increased altitude during bolus O_2 delivery, although not paired with a portable ventilator[9].

As with the previously detailed work, minute ventilation affected delivered FiO_2 in our study. Minute ventilation in our testing conditions range was 7.5 – 14 L/min. Our study results showed that the highest FiO_2 was consistently delivered with the 731 at all test conditions and with the SAVe II at 2 test conditions. Limited minute ventilation (maximum 8 L/min) and PEEP (maximum 10 cm H2O) capabilities prevented testing the SAVe II at all test conditions. Ventilator performance characteristics and O2 bleed-in mechanisms result in varied FiO_2 delivery. Both of the ventilators utilize a compressor to deliver breaths, provide no bias flow and have large reservoirs attached to the air inlet. The 731 uses a 3L reservoir bag and the SAVe II uses 72-inch corrugated tubing as a reservoir, both attached directly to the respective ventilator's air inlet. This method of reservoir use has been shown to provide the highest delivered FiO_2 when using continuous flow O_2[13]. The combination of no bias flow and maximized reservoir use results in the highest delivered FiO_2 as shown in our study. The T1 and VOCSN both utilize a blower to generate gas flow and bias flow to facilitate patient breath triggering. The T1 generates a bias flow of 3 L/min[18]. The VOCSN generates a minimum bias flow of 5 L/min and automatically adjusts to flow trigger + 2 L/min to a maximum of 10 L/min[19]. Flow triggering for the VOCSN testing was set at 2 L/min, consequently bias flow was 5 L/min. O_2 is bled directly into a designated port on each device. The internal reservoir in the devices is presumably much smaller than the reservoirs utilized by the 731 and SAVe II. Although these devices likely allow easier patient triggering, the lack of a large reservoir and continuous bias flow wasting the bled-in O_2, resulted in a lower FiO_2 [13].

The VOCSN was also tested utilizing the integrated O_2 concentrator to generate O_2. The device utilizes pulsed dose technology to deliver the reported equivalent of 0.5 – 6 L/min continuous flow oxygen or up to 40% FiO_2. To be comparable to the SAROS POC, 3 and 6 L/min equivalent pulsed dose settings were used for the evaluation. Bolus doses of oxygen are delivered near the patient connector via an integrated O_2 tube that is optional with the active circuit was used for testing. The O_2 bolus is injected at the beginning of the ventilator delivered breath and is not subject to dilution by bias flow which results in a greater percentage of O_2 reaching the TTL. Our previous work in a porcine model demonstrated that injecting the O_2 bolus just before or as close to the beginning of the breath as possible produced the highest oxygenation by maximizing bolus O_2 efficiency.[14] It has been shown that the pulsed dose equivalent to continuous flow O_2 produced a lower FiO_2 in a bench model although the differences may not be clinically important.[3,4]

6.0 CONCLUSIONS

Oxygen delivery utilizing POCs is dependent upon multiple factors including ventilator operating characteristics, ventilator settings, altitude, and the use of pulsed dose or continuous flow O_2. In this study, the Zoll 731 consistently delivered the highest FiO_2 at all testing conditions likely due to the lack of bias flow and a larger reservoir. Careful patient selection and realizing device capabilities/limitations is paramount to providing safe mechanical ventilation using the POC method of O_2 delivery.

7.0 REFERENCES

1. Barnes SL, Branson R, Gallo LA, Beck G, Johannigman JA. En-route care in the air: snapshot of mechanical ventilation at 37,000 feet. J Trauma 2008;64(2 Suppl):S129-34; discussion S134-5. doi: 10.1097/TA.0b013e318160a5b4. PMID: 18376155.
2. Sequal SAROS specifications. http://files.caireinc.com/CutSheets-Lit/ML-CONC0020.pdf
3. Chen JZ, Katz IM, Pichelin M, Zhu K, Caillibotte G, Finlay WH, Martin AR. In vitro-in silico comparison of pulsed oxygen delivery from portable oxygen concentrators versus continuous flow oxygen delivery. Respir Care 2019;64(2):117-129. doi: 10.4187/respcare.06359. Epub 2019 Jan 29. PMID: 30696754.
4. Chatburn RL, Williams TJ. Performance comparison of 4 portable oxygen concentrators. Respir Care 2010;55(4):433-42. Erratum in: Respir Care. 2010 Jun;55(6):789. PMID: 20406511.
5. Bunel V, Shoukri A, Choin F, Roblin S, Smith C, Similowski T, Morélot-Panzini C, Gonzalez J. Bench evaluation of four portable oxygen concentrators under different conditions representing altitudes of 2438, 4200, and 8000 m. High Alt Med Biol 2016; 17(4):370-374. doi: 10.1089/ham.2016.0056. PMID: 27959667.
6. Litch JA, Bishop RA. Oxygen concentrators for the delivery of supplemental oxygen in remote high-altitude areas. Wilderness Environ Med 2000;11(3):189-91. doi: 10.1580/1080-6032(2000)011[0189:ocftdo]2.3.co;2. PMID: 11055565.
7. Sakaue H, Suto T, Kimura M, Narahara S, Sato T, Tobe M, Aso C, Kakinuma T, Hardy-Yamada M, Saito S. Oxygen inhalation using an oxygen concentrator in a low-pressure environment outside of a hospital. Am J Emerg Med 2008;26(9):981-4. doi: 10.1016/j.ajem.2007.12.009. PMID: 19091263.
8. Fischer R, Wanka ER, Einhaeupl F, Voll K, Schiffl H, Lang SM, Gruss M, Ferrari U. Comparison of portable oxygen concentrators in a simulated airplane environment. Respir Med 2013;107(1):147-9. doi: 10.1016/j.rmed.2012.10.001. Epub 2012 Oct 22. PMID:

23085214.

9. Blakeman TC, Rodriquez D Jr, Britton TJ, Johannigman JA, Petro MC, Branson RD. Evaluation of oxygen concentrators and chemical oxygen generators at altitude and temperature extremes. Mil Med 2016;181(5 Suppl):160-8. doi: 10.7205/MILMED-D-15-00130. PMID: 27168568.
10. Bordes J, Erwan d'Aranda, Savoie PH, Montcriol A, Goutorbe P, Kaiser E. FiO_2 delivered by a turbine portable ventilator with an oxygen concentrator in an Austere environment. J Emerg Med 2014;47(3):306-12. doi: 10.1016/j.jemermed.2014.04.033. Epub 2014 Jun 18. PMID: 24950943.
11. d'Aranda E, Bordes J, Bourgeois B, Clay J, Esnault P, Cungi PJ, Goutorbe P, Kaiser E, Meaudre E. Fraction of inspired oxygen delivered by Elisée™ 350 turbine transport ventilator with a portable oxygen concentrator in an austere environment. J Spec Oper Med 2016;16(3):30-35. PMID: 27734439.
12. Cardinale M, Cungi PJ, Bordes J, Cohergne F, Schmitt S, Langlois A, Meaudre E, Lacroix G. Maintaining a high inspired oxygen fraction with the Elisée 350 turbine transport ventilator connected to two portable oxygen concentrators in an austere environment. J Trauma Acute Care Surg 2020;89(3):e59-e63. doi: 10.1097/TA.0000000000002792. PMID: 32467466.
13. Rodriquez D Jr, Blakeman TC, Dorlac W, Johannigman JA, Branson RD. Maximizing oxygen delivery during mechanical ventilation with a portable oxygen concentrator. J Trauma. 2010;69 Suppl 1:S87-93. doi: 10.1097/TA.0b013e3181e44b27. PMID: 20622626.
14. Blakeman T, Rodriquez D, Johannigman J, Branson R. Pulsed Dose Oxygen Delivery During mechanical ventilation: impact on oxygenation. Mil Med 2019;184(5-6):e312-e318. doi: 10.1093/milmed/usy362. PMID: 30535267.
15. Reynolds PC. Oxygen supplementation of the Impact 754 ventilator. Mil Med 2002; 167(3):196-9. PMID: 11901565.
16. Gustafson JD, Yang S, Blakeman TC, Dorlac WC, Branson R. Pulsed dosed delivery of

oxygen in mechanically ventilated pigs with acute lung injury. J Trauma Acute Care Surg 2013;75(5):775-9. doi: 10.1097/TA.0b013e3182a9252e. PMID: 24158194.

17. Rybak M, Hyffman LC, Nahouraii R, Loden J, Gonzales M, Wilson R, Danielson PD. Ultraportable oxygen concentrator use in U.S. army special operations forward area survey: a proof of concept in multiple environments. Mil Med 2017;182(1/2):e1649-e1652. doi: 10.7205/MILMED-D-16-00100. PMID: 28051988.

18. Hamilton T1 Operator's Manual. Retrieved September 14, 2021 from https://www.hamilton-medical.com/dam/jcr:bef584f1-2fad-448c-81de-e83921f412da/HAMILTON-T1-ops-manual-SW2.2.x-en-USA-10078282.00.pdf

19. VOCSN clinical and technical manual. Retrieved September 14, 2021 from https://www.venteclife.com/assets/Resources/VOCSN_Clinical_Manual.pdf

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

%	percent
CCATT	Critical Care Air Transport Team
cm H_2O	centimeter of water
FiO_2	Free Inspired Oxygen
ft	feet
L/min	Liters/minute
kg	kilogram
mL	milliliters
O_2	oxygen
PEEP	Positive End Expiratory Pressure
POC	portable oxygen concentrator
TTL	Training Test Lung
V_T	volume