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Closed Loop Control of Oxygen Delivery and Oxygen Generation

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14. ABSTRACT

Maintenance of adequate oxygenation and prevention of hypoxemia are the primary goals for the battlefield casualty, but in military operations, oxygen is a limited resource to be conserved. A portable oxygen concentrator has the advantage of operating solely from electrical power and therefore is a never-exhausting supply of oxygen. Our previous bench work demonstrated that the pulsed dose setting of the concentrator can be used in concert with the ventilator to maximize oxygen delivery. We evaluated this ventilator/ concentrator system with closed loop control of oxygen output in a porcine model. The Zoll 731 portable ventilator and Sequal Saros portable oxygen concentrator were used for this study and were connected via a USB cable to allow communication. The ventilator was modified to allow closed loop control of oxygen based on the oxygen saturation (SpO_2) via the integral pulse oximetry sensor. Twelve pigs were used for the evaluation. The animals were placed on a ventilator on 100% fraction of inspired oxygen (FIO_2) and lung injury was induced by warmed saline lavage via the endotracheal tube until partial pressure of oxygen (PaO_2)/FIO_2 decreased to < 100. The pigs were then placed on the ventilator/concentrator system and allowed to adjust the oxygen autonomously to determine if the target SpO_2 could be maintained. Positive end-expiratory pressure (PEEP) was started at 5 cm H_2O for all animals and increased as needed if SpO_2 was ≤ 80% for ≥ 10 minutes or < 88% for > 30 minutes. Arterial blood gases were drawn every 30 minutes for 2 hours to verify the PaO_2 and the SpO_2/ arterial oxygen saturation correlation. All animals survived the study. Mean PaO_2/FIO_2 was 477 ± 61 before lung lavage and 67 ± 8 after lung lavage ($p < 0.001$), representing severe acute respiratory distress syndrome. Thirty minutes after placing the animals on the ventilator/concentrator system, the bolus size range was 64-96 mL and 16-96 mL after 2 hours ($p = 0.02$). The SpO_2 range was 81-95% after 30 minutes and 94-98% after 2 hours ($p = 0.05$). PEEP range was 5-14 cm H_2O. The SpO_2 to arterial oxygen saturation difference was ≤ 4% throughout the evaluation. The ventilator/concentrator system was able to manage oxygenation of severely injured lungs in a porcine model. This was accomplished by injecting oxygen boluses at the front end of the ventilator breath and appropriate use of PEEP to maximize oxygen delivery at the alveolar level. This proof-of-concept ventilator system may prove to be of use in situations where high pressure oxygen is unavailable but electricity is accessible. Clinical trials in humans would be the next step in validating this system.

15. SUBJECT TERMS
Closed loop control, oxygen generation, oxygen concentration, ventilation

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1.0 EXECUTIVE SUMMARY

Adequate oxygenation is one of the primary goals of mechanical ventilation. Maintenance of adequate oxygenation and prevention of hypoxemia are the primary goals for the battlefield casualty, but military operations have unique concerns. In military operations, oxygen is a limited resource to be conserved. The logistical considerations required to provide and sustain oxygen resources in the forward areas are considerable. A portable oxygen concentrator has the advantage of operating solely from electrical power and therefore is a never-exhausting supply of oxygen. Our previous bench work demonstrated that the pulsed dose setting of the concentrator can be used in concert with the ventilator to maximize oxygen delivery. We evaluated this ventilator/concentrator system with closed loop control of oxygen output in a porcine model.

The Zoll 731 portable ventilator and Sequal Saros portable oxygen concentrator were used for this study. The ventilator and concentrator were connected via a USB cable to allow communication. The ventilator was modified to allow closed loop control of oxygen based on the oxygen saturation (SpO_2) via the integral pulse oximetry sensor. The ventilator communicates with the concentrator to increase or decrease oxygen bolus size to maintain a target SpO_2 of 94%. Bolus sizes range from 16-96 mL in 16-mL increments. The oxygen bolus was injected into the ventilator circuit at the patient connector. Six pigs were used for the evaluation. The animals were placed on a ventilator on 100% fraction of inspired oxygen (FIO_2) and lung injury was induced by warmed saline lavage via the endotracheal tube until partial pressure of oxygen (PaO_2)/FIO_2 decreased to < 100. The pigs were then placed on the ventilator/concentrator system and allowed to adjust the oxygen autonomously to determine if the target SpO_2 could be maintained. Positive end-expiratory pressure (PEEP) was started at 5 cm H_2O for all animals and increased as needed if SpO_2 was ≤ 90% for ≥ 30 minutes. Arterial blood gases were drawn every 30 minutes for 2 hours to verify the PaO_2 and the SpO_2/arterial oxygen saturation (SaO_2) correlation.

All animals survived the study. Mean PaO_2/FIO_2 was 477 ± 61 before lung lavage and 67 ± 8 after lung lavage ($p < 0.001$), representing severe acute respiratory distress syndrome. Thirty minutes after placing the animals on the ventilator/concentrator system, the bolus size range was 64-96 mL and 16-96 mL after 2 hours ($p = 0.02$). The SpO_2 range was 81-95% after 30 minutes and 94-98% after 2 hours ($p = 0.05$). PEEP range was 5-14 cm H_2O. The SpO_2 to SaO_2 difference was ≤ 4% throughout the evaluation.

The ventilator/concentrator system was able to manage oxygenation of severely injured lungs in a porcine model. This was accomplished by injecting oxygen boluses at the front end of the ventilator breath and appropriate use of PEEP to maximize oxygen delivery at the alveolar level. This proof of concept ventilator system may prove to be of use in situations where high pressure oxygen is unavailable but electricity is accessible. Clinical trials in humans would be the next step in validating this system.

2.0 BACKGROUND

Achieving adequate oxygenation is one of the primary goals of mechanical ventilation. This goal is accomplished through the adjustment of fraction of inspired oxygen concentration (FIO_2), positive end-expiratory pressure (PEEP), and mean airway pressure. Titration of these variables is guided by continuous noninvasive monitoring of oxygen saturation by pulse

oximetry (SpO_2) and intermittent arterial blood sampling for arterial oxygen tension (partial pressure of oxygen [PaO_2]) and measured arterial oxygen saturation (SaO_2). In adults, adequate oxygenation is typically considered an $SaO_2 > 90\%$ and $PaO_2 > 60$ mmHg. PEEP may also be guided through assessment of pulmonary mechanics, oxygen (O_2) delivery, intrapulmonary shunt, and cardiac output.

While maintenance of adequate oxygenation and prevention of hypoxemia are the primary goals for the battlefield casualty, military operations have unique concerns. In civilian U.S. hospitals, under normal conditions, oxygen reserves are plentiful. In military operations, however, oxygen is a limited resource to be conserved. It has been estimated that oxygen containers and oxygen generation equipment are approximately 15-30% of the entire logistical footprint of weight and space (cube) necessary to provide medical care in the field during combat operations. Little has been studied regarding the use of portable oxygen concentrators (POCs) in austere environments to provide low to moderate levels of oxygen to ventilated patients. Autonomous control of FIO_2 has been accomplished by a number of investigators, primarily in the neonatal population where the oxygenation goals include avoidance of hypoxemia and hyperoxemia. We evaluated a portable ventilator/POC system using autonomous control of oxygen delivery in a porcine model.

3.0 METHODS

This Institutional Animal Care and Use Committee-approved study was conducted in the University of Cincinnati Center for Surgical Innovation using 18 37- to 42-kg female Yorkshire pigs (6 for each experiment). Each animal was intubated and sedated using a continuous infusion of propofol and instrumented with a femoral arterial line to facilitate arterial blood gas sampling.

3.1 System Description

Three different experiments were conducted within this project. Each experiment was conducted using the Zoll 731 series portable ventilator (Zoll Medical Corp., Chelmsford, MA) and a Sequal Saros POC (Chart Industries, Ball Ground, GA) (Figure 1). An engineering group (Sparx Engineering, Manvel, TX) created a data output port in the Saros to enable a connection between the 731 data port so the two devices could "communicate." The Saros O_2 output tubing was connected to a bleed-in port on the ventilator circuit just before the patient connection at the endotracheal tube. For all experiments, the Saros was operated in bolus mode. The maximum output of the POC was 3 lpm, with a bolus range of 16-96 mL in 16-mL increments at an FIO_2 of 93% ± 3%. The circuit boards and firmware were modified in both devices to allow the 731 to tell the Saros when to give an oxygen bolus. The system utilized a closed loop algorithm that compared the SpO_2 value measured noninvasively from the animal to the target SpO_2 of 94% to determine the size of the oxygen bolus to be given. The bolus size was increased or decreased to maintain the target SpO_2. This ventilator/POC system is unique in that the ventilator was not attached to a high-pressure oxygen source, used an internal compressor using room air to deliver tidal volume (V_T), and relied on the POC as the sole O_2 source.

Figure 1. Zoll 731 ventilator and Saros POC used in the study.

3.1.1 Experiment 1. Oxygen boluses from the Saros are delivered at the beginning of each breath and are pushed into the lungs by the 731 compressor. This experiment was designed to determine when best to deliver the bolus to produce the highest PaO_2. Each device was connected to a computer that controlled both devices, synchronizing the delivery of the pulse dose at various points relative to breath initiation. The system was applied to six pigs with normal lung conditions and consistent size/weight. Timing of a 96-mL oxygen bolus was set at various points before, simultaneously, and after the initiation of the ventilator breath to determine the best PaO_2 in the model. The timing range for bolus delivery relative to V_T delivery was -700 to +150 ms. Arterial blood gases (ABGs) were drawn 20 minutes following a change in pulsed dose timing. Minor adjustments were made to ventilator settings based on ABG results to ensure adequate minute ventilation.

3.1.2 Experiment 2. This experiment was designed to determine the system's ability to maintain adequate oxygenation in a porcine model of severe acute respiratory distress syndrome (ARDS). Acute lung injury was induced in six female swine weighing approximately 40 kg. Pigs were sedated using propofol to ensure no spontaneous respirations and had a femoral arterial line placed to monitor blood pressure and to facilitate blood draws. The ventilator was set to 100% O_2 concentration, V_T 10 mL/kg, and respiratory rate to achieve a pH of 7.35-7.45. Warm normal saline (37°C) was instilled into the lungs by gravity using 48 inches of corrugated tubing connected to the endotracheal tube, 200-400 mL at a time until 1 liter was instilled or SpO_2 decreased to ≤ 90%. The saline was allowed to remain in the lungs for 3-5 minutes and then was drained by gravity. The animals were allowed to recover for 5 minutes to determine the SpO_2 and corresponding level of lung injury. This process was repeated until the SpO_2 after the recovery period remained 90-92% on 100% O_2. To induce the lung injury, 3-4 liters of normal

saline were required. ABGs were drawn at the end of the lavage to verify the level of lung injury. The pigs were then placed on the ventilator/POC closed loop system for 2 hours. During the 2-hour period following lung injury, if the oxygen bolus from the POC was at the maximum dose and SpO_2 remained below 80% for > 10 minutes, PEEP was increased as needed to increase SpO_2. If SpO_2 remained < 80% for more than 30 minutes with the POC at the maximum dose, PEEP was further increased until SpO_2 was ≥ 88%. ABGs were drawn every 30 minutes to assess oxygenation and ventilation.

3.1.3 Experiment 3. This experiment used the same procedures as the previous experiment with the exception of a different concentrator scheme. The POC firmware and software were altered to deliver bolus sizes in 1-mL increments instead of 16-mL increments as in the previous experiment. The lung injury model and procedures were identical to the previous experiment.

3.2 Statistical Analysis

POC bolus size, SpO_2, and PEEP at each time point utilizing the ventilator/POC system using 1-mL bolus increments were compared to the system utilizing 16-mL increments using a two-tailed Student's t-test. A p-value < 0.05 was considered significant.

4.0 RESULTS

4.1 Experiment 1

Figure 2 shows the timing in bolus dose relative to V_T delivery and the corresponding PaO_2 for six porcine models. The oxygen bolus injected into the ventilator circuit 300 ms before breath delivery provided the highest PaO_2.

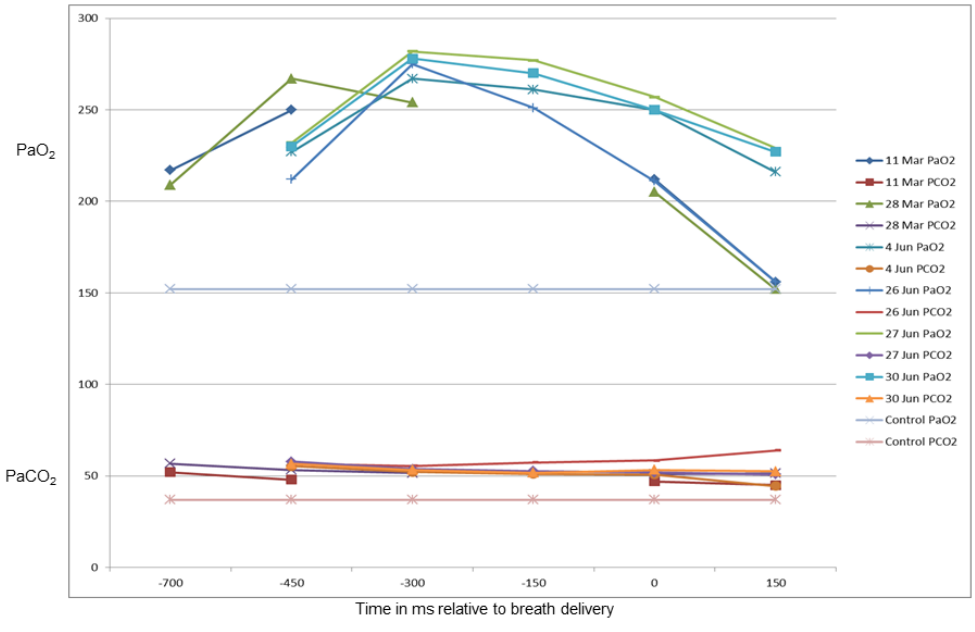

Figure 2. Timing in bolus dose relative to V_T delivery and corresponding PaO_2.

4.2 Experiments 2 & 3

After switching from 100% O_2 to the ventilator/POC system, all lung-injured animals' SpO_2 initially decreased to < 88%, requiring the POC to increase to the highest bolus dose (96 mL). Table 1 shows that at the 30-minute time point the SpO_2 with all animals was > 80%. Bolus dose range was 64-96 mL. At the end of the 2-hour study period, SpO_2 range was 94-98% and the bolus dose range was 16-96 mL. PEEP settings at each time point are shown in the table. Differences in SpO_2, bolus dose, and PEEP between the 1-mL-increment and 16-mL-increment POC bolus dose systems were not statistically significant ($p > 0.05$) at the 30-minute and 2-hour time points. At the 60- and 90-minute time points, SpO_2 was statistically significant ($p < 0.05$) but was not considered clinically important, since SpO_2 was ≥ 91%. Bolus dose and PEEP were not statistically significant at these time points (data not shown). Figure 3 shows bolus size, SpO_2, and PEEP settings throughout the 2-hour study period with the ventilator/POC system using 1-mL bolus increments in one animal. Figure 4 shows the same parameters with the system using 16-mL bolus increments in one animal.

Table 1. Pre- and Post-Lung Injury PaO_2/FIO_2 (P/F) and POC Bolus Sizes, SpO_2, and PEEP at 30 and 120 Minutes Post-Lung Injury

Pig No.	Baseline P/F	Post-Lavage P/F	30 Minutes			120 Minutes		
			Bolus (mL)	SpO_2 (%)	PEEP	Bolus (mL)	SpO_2 (%)	PEEP
1-mL Bolus Increments								
1	490	73	96	85	8	24	94	10
2	499	82	95	95	5	96	96	10
3	496	84	94	95	5	26	96	5
4	555	97	96	91	5	19	95	8
5	543	64	96	91	5	43	97	10
6	461	71	96	92	10	40	95	10
16-mL Bolus Increments								
1	470	78	96	90	5	32	94	10
2	499	75	96	95	5	16	95	5
3	516	64	96	91	8	96	95	14
4	466	60	96	81	8	64	95	14
5	465	63	96	81	5	80	98	12
6	545	61	64	95	10	16	95	10

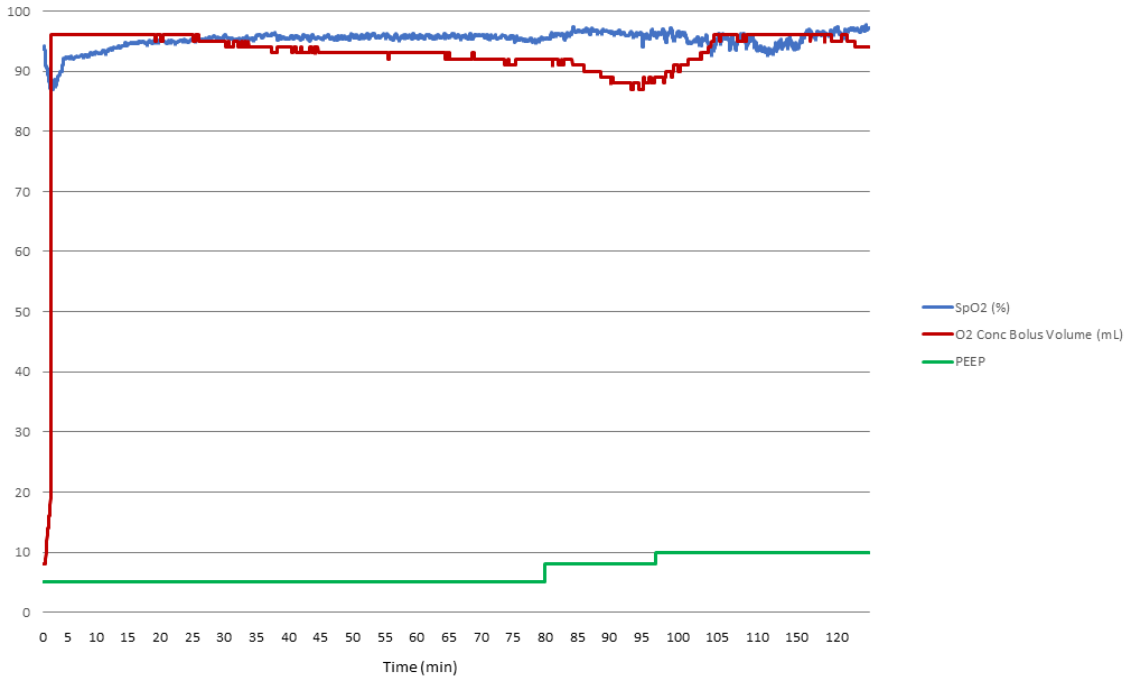

Figure 3. Bolus size, SpO_2, and PEEP settings throughout the 2-h study period with the ventilator/POC system using 1-mL bolus increments.

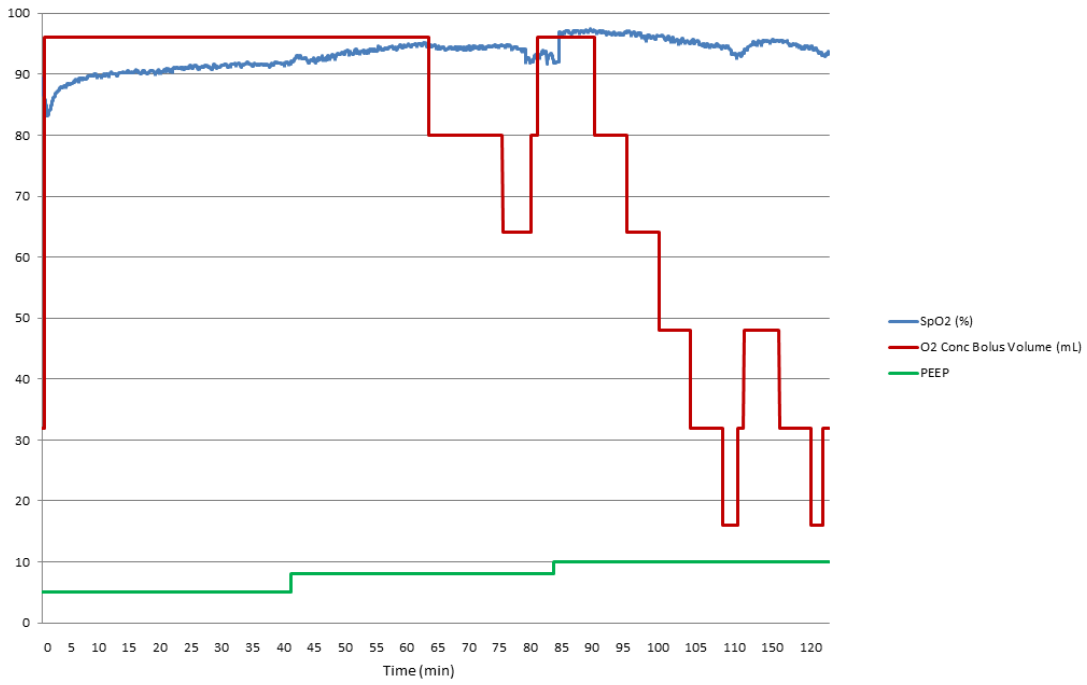

Figure 4. Bolus size, SpO_2, and PEEP settings throughout the 2-h study period with the ventilator/POC system using 16-mL bolus increments.

5.0 DISCUSSION

Oxygen concentrators are widely used for patients in the home setting who require supplemental O_2 due to chronic lung disease [1]. These concentrators were large devices that were meant to be stationary. In developing and resource-constrained countries, concentrators are becoming increasingly popular due to the cost savings as compared to pressurized cylinder systems [2,3]. With the development of POCs in the early 21st century, the portability of an oxygen source enabled patients receiving long-term O_2 therapy to ambulate easier and more economically than using cylinders [4].

While POCs have become the standard for providing home O_2, other potential uses have emerged. Maintenance of adequate oxygenation and prevention of hypoxemia are the primary goals for the battlefield casualty, although military operations have unique concerns. In civilian U.S. hospitals, under normal conditions, O_2 reserves are plentiful. In military operations, however, O_2 is a limited resource to be conserved. During deployed military medical operations, the logistical considerations required to provide and sustain oxygen resources in the forward areas are considerable. Oxygen containers and O_2 generation equipment are a significant portion of the entire logistical footprint of weight and cube necessary to provide medical care in the field during combat operations. These considerations become even more acutely focused during the missions of the Critical Care Air Transport Teams (CCATTs) employed by the U.S. Air Force. A CCATT is a self-carried, three-person team (physician, nurse, respiratory therapist) responsible for providing en route care during all phases of operations. The concept of operations calls for the ability of the CCATT to provide sustained medical support and en route care for up to three intubated patients and/or a total mission of six critically ill patients. This concept of operations includes the necessity of carrying and moving the O_2 resources necessary to support this mission. CCATT mission length is variable depending upon the tactical and strategic consideration(s) of the theater. During current operations in support of Operation Enduring Freedom and Operation Iraqi Freedom, the typical mission profile may readily extend into the 8- to 12-hour range. The necessity of accounting for potential required oxygen resources as well as the physical transport of O_2 tanks and/or liquid oxygen is an important component of any CCATT mission. Mission planning commonly involves a calculation of required O_2 needs and then doubling that value as a margin of safety [5].

Given the preceding considerations, it would seem apparent that O_2 conservation takes on greater importance during military operations. In far-forward areas and during transport, the goals of O_2 therapy are to prevent hypoxemia, ensure adequate arterial oxygenation, and minimize O_2 usage. Little has been studied regarding the use of POCs in austere environments to provide low to moderate levels of O_2 to ventilated patients. A POC has the advantage of operating solely from electrical power and, therefore, is a never-exhausting resource. The POC can be used in a similar fashion to traditional low flow O_2, adding O_2 to a reservoir bag. Our past work demonstrated that the pulse dosed setting of the concentrator could be used in concert with the ventilator to maximize the O_2 delivered in an animal model [6]. With this method, a pulse volume of O_2 is synchronized with the ventilator breath delivery, although this requires manual adjustment by the caregiver.

To our knowledge, this is the first study to evaluate the use of a ventilator/POC system using closed loop technology. Our study showed that this system was able to manage oxygenation using a POC to provide O_2 in conjunction with the appropriate use of PEEP in a severe ARDS animal model with manipulation of the POC or ventilator required by the caregiver

to adjust oxygenation. Unlike the prior system, the current ventilator/POC system utilized electronic communication between the ventilator and POC to automatically adjust both ventilator V_T and POC output. Frontloading the ventilator breath with 93% ± 3% bolus dose O_2 allows for maximizing the 3-lpm POC output by getting a higher O_2 concentration to the alveoli [7] as opposed to blending the O_2 with air as it enters the ventilator intake (Figure 5). POC in bolus mode to deliver O_2 uses less power than when in continuous flow mode, which conserves battery power and increases efficiency that may be important if alternating current power is not initially available [7,8].

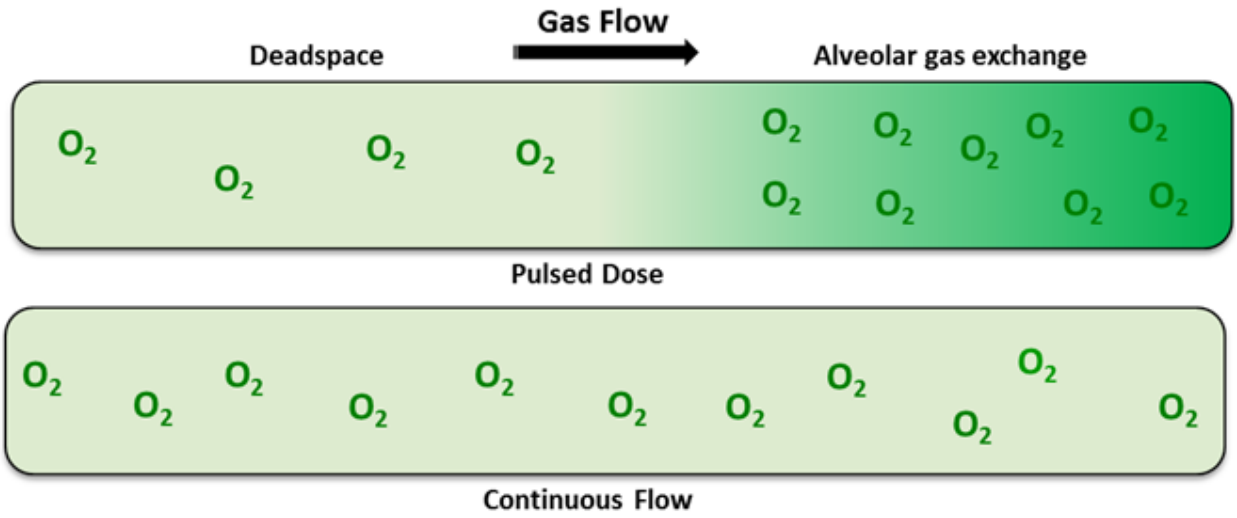

Figure 5. Difference in O_2 concentration at the beginning of the ventilator breath with bolus dose vs. O_2 concentration with continuous flow O_2.

This current study showed that the SpO_2 decreased to > 88% in all animals when placed on the ventilator/POC system. The reason for this is twofold. First, during the lung injury, the animals were receiving 100% O_2 via a ventilator receiving O_2 from a high-pressure gas source. The POC delivers 93% ± 3% O_2; therefore, depending on the respiratory rate set on the ventilator, there could be as much as a 10% decrease in O_2. Second, the POC started at the lowest bolus dose and increased as needed in response to the SpO_2 value. As a safety measure, if SpO_2 decreased to < 88% for more than 10 seconds, the ventilator/POC algorithm automatically increased the O_2 bolus to the maximum dose (96 mL). Although this decrease in oxygenation occurred, at the 30-minute time point 9 of 12 animals had SpO_2 values ≥ 90% and at the 60-minute time point the SpO_2 in all animals was ≥ 93%.

6.0 CONCLUSIONS

Our study shows that either a ventilator/POC closed loop system using a 1-mL- or 16-mL-increment O_2 bolus from the Saros concentrator in addition to appropriate use of PEEP can adequately oxygenate swine in a lung injury model of severe ARDS. In contrast to our previous work, the ability of the two devices that make up the system to electronically communicate allows true closed loop control of oxygenation in addition to automatically adjusting ventilator V_T to accommodate POC bolus size without increasing delivered V_T. This

could allow a caregiver in an austere environment to focus on other tasks involved in patient care without having to closely monitor and adjust O_2 to achieve adequate oxygenation. The way forward is to further refine the closed loop algorithm to increase functionality of the system and move forward with clinical trials in humans.

7.0 REFERENCES

1. Gould GA, Scott W, Hayhurst MD, Flenley DC. Technical and clinical assessment of oxygen concentrators. Thorax. 1985; 40(11):811-816.
2. Dobson MB. Oxygen concentrators for the smaller hospital--a review. Trap Doct. 1992; 22(2):56-58.
3. Dobson MB. Oxygen concentrators offer cost savings for developing countries. A study based on Papua New Guinea. Anaesthesia. 1991; 46(3):217-219.
4. Wilson PM. Portable oxygen: a user's perspective. Concentrators: portable and transportable. [Accessed 8 Aug 2017]. Available from http://69.72.148.165/july.html.
5. Rice DH, Kotti G, Beninati W. Clinical review: critical care transport and austere critical care. Crit Care. 2008; 12(2):207.
6. 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):775-779.
7. 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-S93.
8. Gangidine MM, Blakeman TC, Branson RD, Johannigman JA. System design verification for closed loop control of oxygenation with concentrator integration. Mil Med. 2016; 181(5 Suppl):177-183.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

ABG	arterial blood gas
CCATT	Critical Care Air Transport Team
FIO_2	fraction of inspired oxygen
O_2	oxygen
PaO_2	partial pressure of oxygen
PEEP	positive end-expiratory pressure
POC	portable oxygen concentrator
SaO_2	arterial oxygen saturation
SpO_2	oxygen saturation by pulse oximetry
V_T	tidal volume