Ventilating Two Subjects with One Ventilator: Achievable but not Advisable

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Abstract

Background: The world is in the midst of the COVID-19 viral pandemic and the number of patients requiring mechanical ventilation may exceed the number of ventilators available. New information is being sought on the feasibility of using one ventilator on multiple patients should the need arise. In this study, we hypothesized that two rabbits could be simultaneously mechanically ventilated using a simple, readily available, dual circuit.

Methods: Two pairs of New Zealand White rabbits (n=4) were anesthetized and hooked up to a simple dual circuit and ventilated in the Airway Pressure Release Ventilation mode. Arterial and venous lines were placed for arterial blood gases, hemodynamic monitoring and fluid administration. Following one hour of ventilation, a surfactant washout was performed and mechanical ventilation resumed. Animals were euthanized after an additional one hour of ventilation.

Results: Both Pairs of rabbits had a similar pre-injury P_aO_2/F_iO_2 ratio. Following injury, all rabbits had a decline in P_aO_2/F_iO_2 with 2 maintaining a P_aO_2/F_iO_2 ratio consistent with moderate ARDS, 1 consistent with mild and 1 return to normal. Both Pairs of rabbits had a similar pre-injury P_aCO_2 . Rabbits in Pair 1 maintained similar arterial carbon dioxide (P_aCO_2) levels following ARDS. Pair 2 showed an increase in P_aCO_2 with ARDS due to the much higher P_aCO_2 in the rabbit with the more severe lung injury.

Conclusion: A dual ventilator circuit can be constructed from materials in any respiratory therapy department. Using this dual circuit, two animals with ARDS can be oxygenated and ventilation sufficiently to meet current standards.

Introduction

During a pandemic, the number of patients requiring mechanical ventilation may exceed the number of ventilators available, as experienced during previous influenza pandemics,[1] and is expected to occur again given the current trajectory of the COVID-19 pandemic. The recently published guidelines for management of COVID-19 patients [SCCM *U.S. ICU Resource Availability for COVID-19* (<https://sccm.org/Blog/March-2020/United-States-Resource-Availability-for-COVID-19>)] suggest that the most common reason for COVID-19 patient admission to the intensive care unit (ICU) is severe hypoxic respiratory failure necessitating mechanical ventilation. Acute care hospitals in the U.S.A. own an estimated 62,000 full-featured mechanical ventilators with another ~98,000 older or more basic ventilators (<https://sccm.org/Blog/March-2020/United-States-Resource-Availability-for-COVID-19>) that could be pressed into service. It has previously been estimated that a severe pandemic could infect almost 100 million people resulting in approximately 1.5 million patients in the ICU with 750,000 patients requiring mechanical ventilation.[2] A recent American Hospital Association (AHA) estimate for COVID-19 projected that 4.8 million patients would be hospitalized with 1.9 million admitted to the ICU, of which 960,000 would require ventilator support, thereby exceeding the readily available mechanical ventilator capacity by 6-fold.[3]

With New York City cited as the epicenter of the current COVID-19 pandemic in the U.S.A. and Italy foreshadowing the potential ventilator crisis that could occur in New York City, New York State Governor Cuomo has called for nationalization of resources, specifically mechanical ventilators. In fact, recognizing the need for ventilators, ventilator accessories, and other respiratory devices, on March 22, 2020, the U.S. Food and Drug Administration (FDA) issued an immediately in effect guidance outlining a policy intended to help increase availability of ventilators and their accessories as well as other respiratory devices during the COVID-19 pandemic. One strategy to increase the number of ventilators in a crisis is to ventilate more than one patient with the same ventilator.[4-7] However, there is a critical need for a better understanding of how multiple patients supported by a single ventilator would perform in the setting of acute lung injury (ALI) and a need for advanced rescue ventilation strategies, when traditional methods fail.

To accomplish this goal two objectives must be met: 1) a ventilator circuit must be designed that is capable of connecting more than one patient to the ventilator and 2) an optimal ventilation method must be identified that would be most effective at ventilating two or more patients with the same ventilator. Previous studies have investigated multiple circuit designs on test lungs[4, 5, 7] using multiple methods of setting the ventilator various ventilator modes including: Controlled Mandatory Ventilation (CMV),[4] Pressure and Volume Control,[5] and Synchronized Intermittent Mandatory Ventilation (SIMV).[6]

Previous work from our lab has shown the physiologic[8-19] and clinical[20] benefits of the time controlled adaptive ventilation (TCAV) method of setting and adjusting the airway pressure release ventilation (APRV) mode. Briefly, the TCAV method uses the expiratory flow curve to modulate the ventilator settings according to the underlying lung pathology. A prolonged inspiratory phase allows for an equilibration of mean airway pressure, which effectively recruits lung tissue while a brief release phase stabilizes the lung and maintains a normal end expiratory lung volume. To summarize, the TCAV method is an extended Continuous Positive Airway Pressure (CPAP) Phase combined with a very brief Release Phase that is set and adjusted by changes in lung physiology.[21-27] The TCAV method has been shown effective at treating unilateral ALI (pulmonary contusion and pneumonia) where the patient's lungs have significantly different compliance.[28-32] Unilateral lung injury would therefore be similar to ventilating two patients, each with a different lung compliance, on one ventilator and suggest that TCAV can simultaneously ventilate two lungs with different compliances. Combined these data suggest that the TCAV method would be highly effective at ventilating two patients with one ventilator using a dual circuit.

Methods

Animal experimentation was performed with the approval of the SUNY Upstate Institution of Animal and Use Committee (IACUC).

Animal Preparation

Two pairs of New Zealand White rabbits (n=4) were anesthetized with ketamine (40mg/kg) and xylazine (6mg/kg) via intramuscular injection with a continuous plane of anesthesia throughout the duration of

the experiment. A tracheostomy was performed with a 3-0 cuffed endotracheal (ET) tube by way of a midline incision. An arterial catheter was placed into the common carotid artery for hemodynamic monitoring and arterial blood gases. The external jugular vein was cannulated and used as the site for fluid administration and maintenance of anesthesia.

Mechanical Ventilation

The pairs of rabbits were placed on a dual respiratory circuit connected to a clinical grade ventilator (Drager Infinity V500) (Fig 1) for two separate experiments. The inspiratory limb of the circuit consisted of a proximal wye-connector that was split to deliver inspiration to a second wye-connector just proximal to the endotracheal tube (ETT) of each animal (Fig 1). The same configuration was constructed on the expiratory limb of the ventilator and connected to the other side of the wye-connector at the ETT (Fig 1).

A dual circuit was chosen, instead of a 3 or 4 patient design due to practicality of translation into the clinical realm. With any multiple circuit system, the patients would ideally have a similar lung compliance in order to ventilate the lung of both patients adequately.

Mechanical ventilation was performed using airway pressure release ventilation (APRV) mode with the time controlled adaptive ventilation (TCAV) method.[21] Initial inspiratory pressure (P_{High}) was selected according to the sizes of the paired animals and was 15cmH₂O for Group 1 (Rabbit 1 3.7kg, Rabbit 2 3.7kg) and 13 cmH₂O in Group 2 (Rabbit 3: 4.1kg, Rabbit 4: 3.4kg). The low pressure (P_{Low}) was set to 0 cmH₂O. The time at P_{High} (T_{High}) was set to 3.0 seconds. The time at P_{Low} (T_{Low}) or Release Phase was set using changes in the slope of the expiratory flow curve, which is a surrogate for the respiratory system compliance (C_{RS}) such that the expiratory flow termination (E_{FT}) is equal to 75% of the peak expiratory flow (E_{FP}): $E_{\text{FP}} \times 0.75 = E_{\text{FT}}$. [21]

Data Collection

Following instrumentation and initiation of mechanical ventilation, pulmonary and hemodynamic parameters were recorded and an arterial blood gas (ABG) was obtained (Baseline). Healthy rabbit lungs were ventilated for 1 hour at which point another arterial blood gas was drawn (Pre-Injury). Following the measurements in normal lungs, injury was induced and measurements repeated (Injury).

Lung Injury

To model ARDS, a surfactant washout was performed using a detergent (Tween-20). A 3% Tween solution (3cc/kg) was instilled into the ETT at the same time for both rabbits. Rabbits were placed back on mechanical ventilation and P_{High} was adjusted to reach baseline tidal volumes (V_t), measured in the normal lung. T_{Low} was adjusted so that expiratory flow (E_F) reached 0 cmH₂O for 10 minutes to exacerbate lung injury with atelectrauma (i.e. collapse and reopening of lung tissue with each breath). After the 10 minute ventilation injury period, an ABG was obtained to confirm a sufficient level of lung

injury (Pre-Injury). T_{Low} was then readjusted to maintain E_{FT} at 75% of (E_{FP}) for the remainder of the study.[21, 27] =

Euthanasia

After 1 hour of ventilation in the injured lung, pulmonary, hemodynamic and ABG data was recorded (End) and the rabbits euthanized via barbiturate overdose.

Results

Hemodynamic data for all four rabbits were similar in both sets with baseline values within the normal range and a steady decrease in heart rate and mean arterial pressure following injury (Table 1).

Oxygenation: Both Pairs of rabbits had a similar pre-injury P_aO_2/F_iO_2 ratio (Table 2). Following injury, all rabbits had a decline in P_aO_2/F_iO_2 with 2 maintaining a P_aO_2/F_iO_2 ratio consistent with moderate ARDS, 1 consistent with mild and 1 return to normal. In Pair 1 both rabbits were sufficiently oxygenated following induction of ARDS, both exhibiting the minimum P_aO_2/F_iO_2 ratio levels established by the ARDS Network (Table 2).[33] In Pair 2 one rabbit had a marked increase in P_aO_2/F_iO_2 ratio over time to near baseline levels (with an end P_aO_2/F_iO_2 of 448.5 as compared with the baseline P_aO_2/F_iO_2 of 485.1) whereas the second rabbit's P_aO_2/F_iO_2 was 124.7. The variability between the two rabbits is consistent with the heterogeneous nature of this direct lung injury model, which models the heterogeneous injury typical of viral-induced ARDS. The second rabbit's P_aO_2/F_iO_2 ratio remained in the acceptable range.[3, 33] Mechanical ventilation of the ARDS lung using the TCAV method resulted in a continual increase in P_aO_2/F_iO_2 ratio demonstrating that both animals can be effectively oxygenated using a single ventilator (from **Injury** to **End**) (Table 2).

Ventilation: Both Pairs of rabbits had a similar pre-injury P_aCO_2 (Table 2). Rabbits in Pair 1 maintained similar arterial carbon dioxide (P_aCO_2) levels following ARDS. Pair 2 showed an increase in P_aCO_2 with ARDS due to the much higher $PaCO_2$ in the rabbit with the more severe lung injury. (Table 2)

Gross lung pathology revealed heterogenous atelectasis typical of ARDS (Fig 2). Analysis of dynamic ventilation show that both lungs were in sync with no obvious over-or under-ventilation in either lung. (Supplemental Video)

Discussion

In this study, we tested an easily assembled dual circuit constructed from connectors and tubing found in all respiratory care departments that will ventilate two patients with one ventilator. In addition, we used the TCAV method of setting and adjusting ARRV since we felt this method would be optimal to ventilate two patients with one ventilator for the following reasons: 1) the TCAV method is an effective treatment for unilateral ALI where the patient's lungs have significantly different compliance and would thus be

similar to ventilating two patients with a different lung compliance on one ventilator and 2) the TCAV method is superior to conventional ventilation methods using high PEEP at reestablishing alveolar homogeneity and size distribution measured in a heterogeneous acute lung injury model.[13] We tested our dual circuit using the TCAV method in an animal ARDS model to replicate the clinical scenario in which the number of patients with severe lung injury exceeds the number of mechanical ventilators available and more than one patient must be ventilated with a single ventilator. Although there was a variability between rabbit pairs on the efficiency of oxygenation and ventilation the blood gases of all animals remained in the acceptable range.[3, 33]

Paladino et al. demonstrated the feasibility of a multi-limb circuit in a sheep model using volume-controlled ventilation[6] over 12 hours, however, they did not test performance of their circuit in a lung injury model or with other modes of ventilation. Other researchers have shown the use of multi-limb circuits in simulation or test lung models [4, 5, 7] but oversimplified single compartment test lung models cannot simulate the complex pathophysiology in a heterogeneously injured lung that occurs with COVID-19 induced ARDS.

In this study we demonstrated the feasibility of utilizing a dual circuit and the TCAV method to adequately oxygenate and ventilate the lungs of two rabbits with ARDS using one ventilator. We postulate to be clinically effective this dual circuit therapy must be applied to patients with similar respiratory system compliance (C_{RS}). One way that patients can be selected as pairs for single ventilator ventilation is by using the Berlin criteria since a post hoc showed that C_{RS} correlated with mortality in mild, moderate, and severe ARDS categories. Thus, grouping patients for paired ventilation using the Berlin criteria (i.e. mild/moderate/severe) should be effective.[34]

The potential for successful ventilation using TCAV is drawn from previously published work from our lab. Kollisch et. al, in a rat surfactant wash out model, demonstrated that TCAV resulted in dynamic homogeneity of sub-pleural alveoli and closely mirrored the dynamics seen in the control lungs. In addition, it was shown that high PEEP increased alveolar recruitment, but with a higher degree of size distribution as compared to the control group.[13]. The prolonged CPAP Phase and brief Release Phase allowed for an equilibrated recruitment across the alveolar surface. It is our belief that the addition of another patient in the circuit would be analogous to adding more airways and alveolar units, with unique compliance, to the lung. The treatment strategy would remain the same, as the CPAP phase allowed for alveolar recruitment and the release phase would allow for ventilation, while maintain end expiratory lung volume due to the brief release time.

Conclusion

In summary, we have shown that a dual ventilator circuit can be easily constructed from materials in any respiratory therapy department. Using this dual circuit and the TCAV method two animals with ARDS can be oxygenated and ventilation sufficiently to meet current standards.[3, 33] We feel that if the number of

patients with COVID-19 induced ARDS exceeds the number of ventilators available and all other options have been exhausted, the dual circuit combined with the TCAV method may be considered.

Limitations: Although this study demonstrates the proof-of-concept that it is possible to maintain adequate gas exchange on two ARDS patients using one ventilator, in our opinion this is not an established or predictable method of durable ventilation. The reliability and safety in critically ill patients remain unknown and is inadequately tested. Although technically possible, the complexities of critically ill patients are the most challenging and unpredictable aspects of ventilating two patients with one ventilator. Therefore, this method should only be considered in the event a hospital has an inadequate number of ventilators and should be utilized for the briefest time possible until dedicated ventilation can be implemented. The complexity of the lung pathophysiology with COVID-19 induced ARDS makes it extremely difficult to mechanically ventilate a single patient, much less two patients on one ventilator.

Declarations

Ethics approval and consent to participate: Animal experimentation was performed with the approval of the SUNY Upstate Institution of Animal and Use Committee (IACUC).

Consent for publication: N/A

Availability of material and data: Data is stored on local hard drives and backed up on cloud based services. Data is available on request.

Competing Interests: MKS, PLA, GFN, and NMH have presented and received honoraria and/or travel reimbursement at event(s) sponsored by Dräger Medical Systems, Inc., outside of the published work and have lectured for Intensive Care On-line Network, Inc. (ICON).

NMH is the founder of ICON, of which PLA is an employee. NMH holds patents on the Time-Controlled Adaptive Ventilation method of initiating, managing, and/or weaning airway pressure release ventilation, as well as controlling a ventilator in accordance with the same, but these patents are not commercialized, licensed, nor royalty producing. The authors maintain that industry had no role in the design and conduct of the study; the collection, management, analysis, or interpretation of the data; nor the preparation, review, or approval of the manuscript.

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Author's contributions:

Design and implementation-JS, SB, GT, NMH

Drafting of Manuscript – JS, GFN, NMH, PLA, MKS

Critical Editing of Manuscript – All authors

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Tables

Table 1. Hemodynamic Data at Baseline and 3 hours following injury [Injury (End)] for all 4 animals.

	Pair 1		Pair 2	
Heart Rate	Rabbit 1	Rabbit 2	Rabbit 3	Rabbit 4
BL	139	147	197	251
End	190	183.0	204	197
MAP	Rabbit 1	Rabbit 2	Rabbit 3	Rabbit 4
BL	77	75	77	53
End	31	33	58	55
Oxygen Saturation	Rabbit 1	Rabbit 2	Rabbit 3	Rabbit 4
BL	100	100	100	100
End	96	99	55	100

Table 2. Blood Gas Data at Baseline and 3 hours following injury (End) for each individual animal.

	Pair 1		Pair 2	
PaO2	Rabbit 1	Rabbit 2	Rabbit 3	Rabbit 4
BL	540.8	523.5	485.1	513
End	48.4	74.3	448.5	124.7
PaCO2	Rabbit 1	Rabbit 2	Rabbit 3	Rabbit 4
BL	39.9	36	51.3	51.5
End	25.5	24.7	32.8	76.5
pH	Rabbit 1	Rabbit 2	Rabbit 3	Rabbit 4
BL	7.48	7.49	7.38	7.35
End	7.49	7.49	7.44	7.20

Figures

Figure 1

A simple dual limb circuit was built using 4 wye connectors. The inspiratory limb (purple hose) is split with a proximal wye connector and connected to the distal wye connector of each patient. The same is done for the expiratory limb (green). A filter is placed between the proximal expiratory wye connector and the ventilator.

Figure 2

A – Pair 1 lungs fixed at 20cmH20; B – Pair 2 lungs fixed at 20cmH20

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [RabbitLungsDualCircuit.m4v](#)