Personalized ventilation to multiple patients using a single ventilator: Description and proof of concept

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Introduction

The current COVID-19 pandemic has led to a demand for mechanical ventilators that has outstripped supply in a number of jurisdictions and threatens to do so in more hospitals in the very near future. To address this terrible dilemma, clinicians have proposed splitting the tidal volume delivered by a ventilator between two or more patients[1,2] and thoughtful guidelines to support its implementation have been developed[3]. The FDA considered the need to expand ventilator capacity sufficiently urgent that it very rapidly provided Emergency Use Authorization for a device that facilitated ventilator sharing.[4]

However, splitting of ventilator output has received widespread criticism. On March 26, 2020, a number of medical societies including the Society for Critical Care Medicine published a *Consensus Statement on Multiple Patients Per Ventilator*[5] advising against the use of the technique citing inherent risks, summarized in Table 1. The major disadvantages they enunciated are a) inability to match ventilatory parameters such as tidal volume (V_T), F_IO_2, and positive end-expiratory pressure (PEEP) to individual patient needs, and (b) a change in respiratory mechanics in one patient adversely affecting ventilation to the co-ventilated patient.

To address this issue, we designed a circuit based on the work of Sommer et al.[6] The circuit is based on the principle that the interdependence between patients could be minimized if each patient was ventilated by their own secondary circuit (i.e., "a bag-in-the-box"), with no direct contact between the individual inspiratory circuits (Figure 1). Each secondary circuit would have its own PEEP valve and its own blender to provide a fresh gas flow (FGF) and F_IO_2. Ventilation to both patients would be driven by a single ventilator in pressure control mode; during inspiration, gas from the ventilator flows into the "boxes" increasing the pressure therein and displacing gas from the flexible "bags" into the patients.

On expiration, gas flows through the expiratory circuit from each patient, mixing in the tubing just before the ventilator's exhalation valve. During this exhalation phase, gas continues to flow from the blender to inflate the "bag" for the next inspiration. Using this configuration, multiple patients would share the same respiratory rate (RR), but there would be no cross contamination of inspiratory airway gases, and individual values of V_T, F_IO_2, and PEEP, would remain substantially constant for each patient, independent of a change in the mechanics or ventilator settings of a co-ventilated patient.

Herein we describe this system and provide detailed instructions on how to assemble it from standard parts that can be found in most hospitals. We document the results of bench testing confirming that V_T and PEEP in one lung are substantially maintained in light of changes in mechanics and PEEP in the other.

Methods

A schematic of the circuit is shown in Figure 1. A detailed description of the parts required and how to assemble the circuit are given in the online Supplement. We used 2 test lungs (QuickLung, InGMAR Medical. Pittsburgh, Pennsylvania, USA), representing patient lungs.

An ICU ventilator (Nellcor Puritan Bennet 840 Ventilator (Covidien, Mansfield, MA, USA)) in pressure control mode (PCV) was used with inspiratory pressure set at 30 cmH_2O. We recorded (BIOPAC systems, Inc MP150) airway pressure and V_T in both lungs, under the following conditions:

1. We examined the effect of different respiratory system compliances (Crs) for the 2 lungs (~15 or ~60 ml/cmH_2O), different PEEP values (~5 or ~20 cmH_2O), and RR (10 or 30 b/min) to determine if we could independently apply different ventilatory strategies for each lung, despite differences in respiratory system mechanics.
2. We assessed whether we could provide a lung protective ventilation strategy to each lung with different PEEP values, V_T, and different driving pressures (ΔP) (peak inspiratory pressure (PIP) minus PEEP). PIP was used to compute ΔP as the constant fresh gas flow creates minimal increases airway pressure even in the absence of ventilator-delivered flow.
3. We also examined the effects of a disconnection from the circuit, or of a sudden occlusion of the endotracheal tube of one lung on the non-affected lung.

For each combination of tests, Crs and PEEP, we increased the FGF to each lung separately until either V_T of 400 ml (roughly corresponding to 6 ml/kg in a patient with a predicted body weight (PBW) of ~70 kg, or to a PIP maximum of 35 cmH_2O, whichever came first.

4. Finally, we assessed whether this system would allow for delivery of reasonable sized V_T in lungs with extremely low Crs.

In terms of monitoring, when the two lungs were being ventilated with their individually allocated strategy, we used the exhaled V_T measured by the ventilator, and then set an alarm limit equal to the total exhaled volume minus the smaller V_T of the 2 test lungs which would alarm if either circuit became disconnected at the endotracheal tube (ETT).

Results

Table 2a shows that it is possible to independently set V_T and PEEP in lungs with substantially different Crs (~15 and ~60 ml/cmH_2O respectively). In a separate experiment we obtained a V_T of 405 ml in a lung with a Crs of 7.0 ml/cmH_2O (Test condition #3; Figure 2a).

Table 2b presents the results of the disconnection of the system and the occlusion of the ETT. The impact on the ventilation to the second test lung was minimal, with less than a 2% change in V_T. The same results were observed when different Crs were set (~10 ml/cmH_2O and ~60 ml/cmH_2O), demonstrating the relative independence of the ventilation pattern of one lung from the other.

When the test lung was disconnected from the circuit, the ventilator's alarm triggered within 2 breaths.

Discussion

We describe a novel system that can reliably ventilate two patients with different respiratory system mechanics and ventilation requirements using a single ventilator. We showed that changes in Crs, V_T and PEEP of one co-ventilated lung minimally affect the ventilation delivered to the other lung.

Current approaches for ventilating two or more patients by splitting the flow of a single ventilator can lead to problems[2,7] as summarized in Table 1. Using the ventilator in the pressure-cycled mode in a split circuit without secondary circuits would provide a consistent tidal volume to one patient despite changes in resistance and compliance in other co-ventilated patients. However, it is not possible to individualize V_T, F_IO_2 and PEEP for each of the patients. Moreover, if one patient becomes disconnected from the circuit, tidal volume will be lost to the other patient. To address these problems, clinicians have developed a detailed protocol and risk mitigation strategy as recently proposed by a group out of New York[3]. This approach can decrease the risks, but it is still not possible to individualize PEEP or F_IO_2, or to optimize V_T in each patient independently.

Our approach of using a secondary circuit for each patient overcomes these problems and addresses the concerns raised by the Societies' joint statement[5] (summarized in Table 1). The V_T each patient receives is determined by the FGF to that patient's circuit, providing complete independence in terms of V_T delivery, even in situations where patients with significant differences in respiratory system mechanics are placed on the system. We also found that ventilation was essentially unaffected by extreme changes of a co-ventilated patient's respiratory mechanics, as demonstrated when we disconnected or clamped the circuit at the lung entrance. Although we performed experiments with two test lungs, this approach is applicable for ventilating 3, 4, or more subjects if the ventilator has the flow capacity to generate sufficient pressure in the ”bag-in-the-box” systems to collapse all of the ”bags”. PEEP can also be individually set with an in-line PEEP valve.

Circuit Limitations

Our approach has a number of important limitations. First, patients must be sedated and paralyzed, and RR and I:E ratios are identical for all patients. Secondly, PEEP levels may be impacted in a manner that is dependent on the FGF to all secondary circuits and the characteristics of the ventilator's expiratory valve. Third, the set-up is not optimized for weaning, and patients would have to be transferred to a separate ventilator for weaning. Fourth, as this is improvised emergency ventilatory support, clinical vigilance is mandatory. The traditional monitored variables of the ventilator are not able to monitor each secondary circuit, but can be used in some ventilators to monitor disconnections at the endotracheal tube of either patient. As such, individualized monitoring for each circuit should be performed using portable devices for F_IO_2, capnography, and airway pressure and flow.

A pressure relief valve in the inspiratory limb of the secondary circuit is required for patient safety. Our data was gathered without the relief valve as some of these valves began to leak gas at pressures below the set threshold pressure and interfered with our proof of concept measurements.

Conclusion

This shared ventilator function is proposed as a "last ditch" ventilatory assist device and not as a preferred ventilation mode. In a time of crisis where resources are limited, we introduce a system of multiple secondary breathing circuits driven by a ventilator in preference to that of simply splitting the breathing circuits, which have been shown to raise multiple risks for patients. It is our hope that neither approach will be needed.

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Table and Figure Legends

Table 1: Potential Problems with using one ventilator for two (or more) patients by splitting the ventilator circuit.

The first column summarizes some of the major problems with using one ventilator with a split circuit to ventilate more than one patient. (Adapted from *Consensus Statement on Multiple Patients Per Ventilator* [5]). The second column summarizes how the "bag-in-the-box" system described in this paper addresses each of these problems.

Table 2a: Summary of results using one ventilator (Nellcor Puritan Bennet 840) in pressure control mode (30 cmH_2O) at 2 different respiratory rates (RR) to ventilate two "bag in the box" circuits (secondary circuits) connected to two lung models with different compliances and different PEEP values.

In the top panel in Test Condition 1 and 2, the fresh gas flows in each ventilator secondary circuit were increased separately until the Peak Inspiratory Pressure (PIP) in the secondary circuit reached 35 cmH_2O or a tidal volume (V_T) of 400 ml, whichever came first. Note that it was possible to provide different V_T and PEEP levels to the two lung models from the same ventilator, even though the compliance of the two lungs were markedly different (~15 vs 60 ml/cmH_2O). In Test Condition 3, we obtained a V_T of 405 ml in a lung with extremely low Crs (7 ml/cmH_2O), and a similar V_T in the other lung with a Crs of 37 ml/cmH_2O.

Table 2b: Summary of results using one ventilator (Nellcor Puritan Bennet 840) in pressure control mode (30 ml/cmH_2O) simulating a disconnect (A: Top panel) of the second patient's circuit or a simulated complete occlusion of the endotracheal tube of the second patient (B: Bottom panel), under differing values of compliance, V_T, and PEEP for the test lung. There were 4 experiments for each intervention, and results are presented for the lung that was not disconnected or occluded. Note that V_T changed less than 2% with the simulated occlusion of the endotracheal tube of the other lung, demonstrating a "worst-case" scenario in terms of the impact of a change in respiratory system mechanics of the second lung.

Figure 1: Schematic diagram of two secondary circuits being driven by a single ventilator. A secondary circuit consists of a “bag in the box” configuration. The “box” in our circuit consisted of a suction cannister with the lid glued to the rim to prevent it dislodging with positive pressure (fully described in URL). This “box” (1) contains two ports. A 2 L anesthetic bag (2) opens to one port, which leads to the patient inspiratory tube. The inspiratory tube also contains a port for fresh gas flow consisting of oxygen or blend of oxygen and air, and a one-way valve (3). The inspiratory tube is connected to the patient via a 3-way wye connector (4) and a HEPA filter. The expiratory tube has a one-way valve, a pressure relief ("pop off") valve at 40 cmH_2O and may contain flow-through mechanical PEEP valves which also function to assure the ”bag” in the box inflates during exhalation; it connects to the expiratory limb of the ventilator (5).

The primary driving circuit from the ventilator: The inspiratory limb of the ventilator is split such that there is one branch for each secondary circuit. Each branch consists of an inspiratory and expiratory tube, connected to a wye piece, which is connected to the second (driving) port of the ”box” (1). The expiratory limb from the wye (6) connects back to the expiratory limb of the ventilator (5). Additional secondary circuits may be added by connecting additional branches of the ventilator primary circuit.

Circuit Caveats:

(1) For the PEEP valves in the expiratory limb of the secondary circuit, one should not use a valve that vents to air as it will decrease the flow of gas returning to the ventilator and may cause the ventilator to alarm. This PEEP valve also ensures that the FGF fills the “bag” rather than flowing out of the circuit with exhaled gas. (2) Higher cumulative FGF will increase the pressure at the ventilator expiratory valve which will be additive to the PEEP applied with the PEEP valves. (3) Note the inspiratory limb of the secondary circuit needs to contain a one-way valve to prevent backflow of expired gas into the ‘bag’. (4) Although, it would seem to be expedient, single duck-billed (non-rebreathing) valves should not be used in the inspiratory and expiratory limbs of the secondary circuit. This would be *very dangerous*, since the duck-billed valves may become stuck in the inspiratory position with high FGF, or with PEEP and will result in breath-stacking.

Table 1

Potential Problems	Solution with current secondary circuits
1. Misdistribution of V_T due to differences in mechanics	
• Volumes would go to the most compliant lung segments.	• V_T not affected by mechanics of co-ventilated lung
• During cardiac arrest, ventilation to all patients would need to be stopped to allow the change to bag ventilation; ventilator would have to be reset for remaining patients.	• V_T not affected by disconnection of other circuit
• Even if all connected patients have the same clinical features at initiation, they could diverge and distribution of gas to each patient would be unequal. Sickest patient would get the smallest V_T and the improving patient would get the largest tidal volume.	• V_T is not affected by mechanics of co-ventilated lung
• Sudden deterioration of a single patient (e.g.,pneumothorax, kinked endotracheal tube), causes the balance of ventilation to be redistributed among patients.	• V_T not affected by obstruction of circuit in co-ventilated lung
• Individual PEEP and FIO_2 cannot be implemented.	• PEEP and FIO_2 can be individualized to each lung
2. Monitoring and alarm issues	
• Monitoring patients and measuring pulmonary mechanics would be challenging, if not impossible.	• Measurement of mechanics is possible
• Alarm monitoring and management would not be feasible.	• Many alarms are feasible
• Additional external monitoring would be required. The ventilator monitors the average pressures and volumes.	• Additional monitoring would be required

3. The added circuit volume defeats the operational self-test (the test fails). The clinician would be required to operate the ventilator without a successful test, adding to errors in the measurement.	• Self test proceeds with primary circuit, or series of primary circuits and alarms are valid for the primary circuit. Secondary circuits require their individual pressure circuits and alarms.

Table 2a

Test Condition		Crs ml/cmH_2O	RR /min	Set PEEP cmH_2O	FGF l/min	Measured PEEP cmH_2O	VT ml	PIP cmH_2O	Driving Pressure (PIP-PEEP) cmH_2O
#1	Lung A	18	10	20	8.0	22.5	220	35	12.5
	Lung B	63	10	5	3.3	6.6	401	13	6.4
#2	Lung A	18	30	20	7.0	23.3	211	35	11.7
	Lung B	62	30	5	9.5	9.5	402	16	6.5
#3	Lung A	37	10	5	14.0	11.2	398	22	10.8
	Lung B	7	10	5	>15	8.0	405	56	48.0

Table 2b

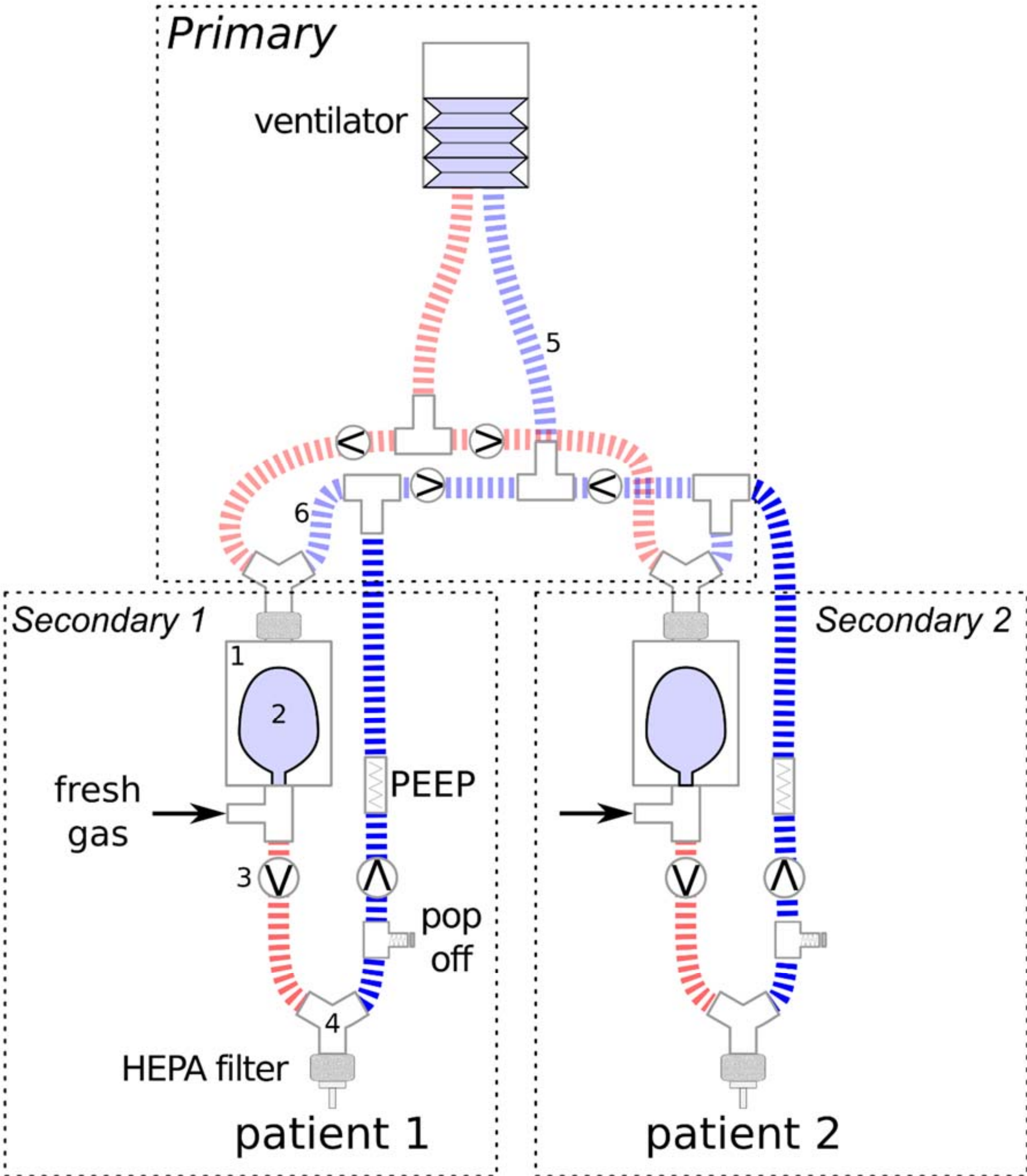
A: IMPACT OF DISCONNECTING ONE PATIENT ON VT AND PEEP OF SECOND PATIENT

Baseline Characteristics		Pre-disconnect values		Post-Disconnect values	
Crs (ml/cmH_2O)	RR (/min)	VT (ml)	PEEP (cmH_2O)	VT (ml)	PEEP (cmH_2O)
10	10	277	20.7	280	20.7
50	10	293	6.2	297	6.2
10	30	267	23.4	269	20.9
50	30	550	10.3	550	10.3

B: IMPACT OF OCCLUDING FLOW TO ONE PATIENT ON V_T AND PEEP OF SECOND PATIENT

Baseline Characteristics		Pre-occlusion values		Post-Occlusion values	
Crs (cmH_2O)	RR (/min)	VT (ml)	PEEP (cmH2O)	VT (ml)	PEEP (cmH_2O)
10	10	272	20.8	274	20.7
50	10	299	7.1	293	7.2
10	30	267	23.0	273	21.8
50	30	606	7.6	594	7.5

Figure


Primary
ventilator
5
6
Secondary 1
1
2
fresh gas
PEEP
3
pop off
4
HEPA filter
patient 1
Secondary 2
patient 2