Personalized Ventilation to Multiple Patients Using a Single Ventilator: Description and Proof of Concept

Jay S. Han, MD, MSc1,2; Azad Mashari, MD1,2; Devin Singh, MD, PhD2; Jose Dianti, MD3,4; Ewan Goligher, MD, PhD4,5; Michael Long, BScH, RRT6; William Ng, MBBS, MMed1,2; Marcin Wasowicz, MD, PhD1,2; David Preiss, MD, PhD7,8; Alex Vesely, MD, MSc9; Robert Kacmarek, PhD, RRT8,10; Shaf Keshavjee, MD11; Laurent Brochard, MD, HDR5,12,13; Joseph A. Fisher, MD1,2; Arthur S. Slutsky, MD5,12,13

Objectives: To design and test a ventilator circuit that can be used for ventilation of two or more patients with a single ventilator, while allowing individualization of tidal volume, fractional concentration of oxygen, and positive end-expiratory pressure to each patient, irrespective of the other patient’s respiratory system mechanics.

Design: Description and proof of concept studies.
Settings: Respiratory therapy laboratory.
Subjects: Ventilation of mechanical test lungs.
Interventions: Following a previously advocated design, we used components readily available in our hospital to assemble two “bag-in-a-box” breathing circuits. Each patient circuit consisted of a flexible bag in a rigid container connected via one-way valve to a test lung, along with an inline positive end-expiratory pressure valve, connected to the ventilator’s expiratory limb. Compressed gas fills the bags during “patient” exhalation. During inspiration, gas from the ventilator, in pressure control mode, enters the containers and displaces gas from the bags to the test lungs. We varied tidal volume, “respiratory system” compliance, and positive end-expiratory pressure in one lung and observed the effect on the tidal volume of the other.

Measurements and Main Results: We were able to obtain different tidal volume, dynamic driving pressure, and positive end-expiratory pressure in the two lungs under widely different compliances in both lungs. Complete obstruction, or disconnection at the circuit connection to one test lung, had minimal effect (<5% on average) on the ventilation to the co-ventilated lung.

Conclusions: A secondary circuit “bag-in-the-box” system enables individualized ventilation of two lungs overcoming many of the concerns of ventilating more than one patient with a single ventilator.

Key Words: artificial respiration; coronavirus disease 2019; mechanical ventilation; ventilator

The current coronavirus disease 2019 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 the terrible dilemma that this may raise, clinicians have proposed splitting the tidal volume (Vr) delivered by a ventilator between two
or more patients (1, 2) and thoughtful guidelines to support its implementation have been developed (3). The Food and Drug Administration 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, the 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 which are summarized in Table 1. The major disadvantages they considered can be summarized as follows: 1) inability to match ventilatory variables such as VT, Fio2, and positive end-expiratory pressure (PEEP) to individual patient needs, and 2) a change in respiratory mechanics in one patient would adversely affect ventilation to the co-ventilated patient(s).

To address these issues, we designed a patient ventilation circuit based on the work of Sommer et al (6). The circuit is centered 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 (Fig. 1). Each secondary circuit would have its own PEEP valve and its own blend of oxygen and air to provide a fresh gas flow (FGF) and Fio2. Ventilation to all patients would be driven by a single ventilator in pressure control mode (PCV); 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 blend of air and oxygen to inflate the “bag” for the next inspiration. Using this configuration, co-ventilated patients would share the same respiratory rate (RR) and inspiratory-expiratory (I:E) ratio, but there would be no cross-contamination of inspiratory airway gases. Individual values of VT, Fio2, 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 VT and PEEP in one lung are substantially maintained in light of changes in mechanics and PEEP in the other.

**MATERIALS AND 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 (Supplemental Digital Content 1, http://links.lww.com/CCX/A173). We used two test lungs (QuickLung; InGMAR Medical, Pittsburgh, PA), representing patient lungs.

| TABLE 1. Ventilator Splitting Circuit: Potential Problems and Solutions |
|-------------------------------------------------|
| **Potential Problems** | **Solution With Current Secondary Circuits** |
| 1) Misdistribution of VT due to differences in mechanics | VT not affected by mechanics of co-ventilated lung |
| Volumes would go to the most compliant lung segments | VT not affected by disconnection of other circuit |
| 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 | VT is not affected by mechanics of co-ventilated lung |
| 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. Sicker patient would get the smallest VT, and the improving patient would get the largest VT | VT not affected by obstruction of circuit in 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 | PEEP and Fio2 can be individualized to each lung |
| Individual PEEP and Fio2 cannot be implemented | |
| 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 |

PEEP = positive end-expiratory pressure, VT = tidal volume.

This table describes 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 article addresses each of these problems.
An ICU ventilator (Nellcor Puritan Bennett 840 Ventilator; Covidien, Mansfield, MA) in PCV was used with inspiratory pressure set at 60 cm H₂O. We recorded airway pressure and Vt in both lungs, using the FluxMed Gr (MBMed, Buenos Aires, Argentina) under the following conditions:

1) We examined the effect of different respiratory system compliances (Crs) for the two lungs (10 or 50 mL/cm H₂O), different PEEP values (=5 or =20 cm H₂O), and RR (10 or 30 breaths/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, Vt, and different dynamic driving pressures (∆Ps) (peak inspiratory pressure [PIP]–PEEP). PIP was used to compute ∆P as the constant FGF results in increasing airway pressure, albeit minimal, 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 inspiratory tube of one lung on the Vt of the nonaffected lung.

For each combination of tests, we increased the FGF to each lung separately until the first occurrence of either Vt of 400 mL (roughly corresponding to 6 mL/kg in a patient with a predicted body weight of ≈70 kg) or to a PIP maximum of 40 cm H₂O. FGF was read from the rotameter.

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

When the two lungs were being ventilated with their individually allocated strategy, we used the
Han et al

exhaled Vt as measured by the ventilator, and then set an alarm limit equal to the total exhaled volume minus the smaller Vt of the two test lungs which would alarm if either circuit became disconnected at the endotracheal tube (ETT).

RESULTS

Table 2 shows that it is possible to independently set Vt and PEEP in lungs with substantially different Crs (10 and 50 mL/cm H2O). In extreme conditions, with a Crs of 10 mL/cm H2O, PEEP of 20 and a RR 30, a Vt of 162 mL was delivered. However, this Vt was only limited by our predetermined PIP cutoff of ~40 cm H2O (test condition number 2).

Tables 3 and 4 present 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 relatively small with an average of less than 5% change in Vt. The same results were similar when different Crs were set (10 and 50 mL/cm H2O), 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 two 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, Vt, 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

### TABLE 2. Effect of Fresh Gas Flow, Respiratory Rate, and Positive End-Expiratory Pressure on Tidal Volume of Two Co-Ventilated Lung Models With Disparate Compliance

| Test Condition | Test Lung Compliance (mL/cm H2O) | Respiratory Rate (/min) | Fresh Gas Flow (L/min) | Set PEEP (cm H2O) | Measured PEEP (cm H2O) | Target Vt (mL) | Measured Vt (mL) | Driving Pressure (PIP–PEEP) (cm H2O) |
|---------------|---------------------------------|------------------------|------------------------|--------------------|------------------------|----------------|----------------|-------------------------------------|
| Number 1      | Lung A                          | 10                     | 10                     | 2                  | 20                     | 21             | 400            | 121                   | 42                   | 21                   |
|               | Lung B                          | 50                     | 10                     | 4                  | 5                      | 6              | 400            | 394                   | 17                   | 11                   |
| Number 2      | Lung A                          | 10                     | 30                     | 6                  | 20                     | 21             | 400            | 162                   | 41                   | 20                   |
|               | Lung B                          | 50                     | 30                     | 12                 | 5                      | 8              | 400            | 393                   | 19                   | 11                   |
| Number 3      | Lung A                          | 50                     | 30                     | 12                 | 5                      | 8              | 400            | 390                   | 15                   | 7                    |
|               | Lung B                          | 10                     | 30                     | 9                  | 5                      | 8              | 400            | 262                   | 38                   | 30                   |
| Number 4      | Lung A                          | 50                     | 10                     | 4                  | 5                      | 6              | 400            | 393                   | 16                   | 10                   |
|               | Lung B                          | 10                     | 10                     | 3.5                | 5                      | 6              | 400            | 281                   | 40                   | 34                   |

PEEP = positive end-expiratory pressure, PIP = peak inspiratory pressure, Vt = tidal volume.

This table describes the summary of results using one ventilator (Nellcor Puritan Bennet 840) in pressure control mode (60 cm H2O) at two different respiratory rates 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 conditions 1 and 2, the fresh gas flows in each ventilator secondary circuit were increased separately until the PIP in the secondary circuit reached 40 cm H2O or a Vt of 400 mL, whichever came first. Note that it was possible to provide different Vt and PEEP levels to the two lung models from the same ventilator, even though the compliance of the two lungs were markedly different (10 vs 50 mL/cm H2O).

### TABLE 3. Effect of Disconnection of the Inspiratory Limb of One Co-Ventilated Lung on the Remaining Lung With Disparate Compliances, Respiratory Rates, and Positive End-Expiratory Pressure Settings

| Test Lung No. 2 Condition | Baseline Characteristics | Predisconnect Values | Postdisconnect Values |
|---------------------------|--------------------------|----------------------|-----------------------|
|                           | Respiratory System       | Vt (mL)              | PEEP (cm H2O)         | Vt (mL)              | PEEP (cm H2O) |
|                           | Compliance (mL/cm H2O)   | 145                  | 21                    | 146                  | 21            |
| 1                         | Respiratory Rate (/min)  | 10                   | 10                    | 10                   | 10            |
| 2                         | 145                      | 21                   | 146                  | 21                   |
|                           | 30                       | 30                   | 168                  | 21                   |
| 3                         | 50                       | 10                   | 320                  | 5                    |
| 4                         | 30                       | 30                   | 480                  | 6                    |

PEEP = positive end-expiratory pressure, Vt = tidal volume.

This table describes the summary of results using one ventilator (Nellcor Puritan Bennet 840) in pressure control mode (60 mL/cm H2O) simulating a disconnect of the one patient’s circuit under differing values of compliance, Vt, and PEEP for the test lung. There were four experiments and results are presented for the lung that was not disconnected.
mode in a split circuit without secondary circuits would provide a consistent Vt to one patient despite changes in resistance and compliance in other co-ventilated patients. However, it is not possible to individualize Vt, Fio2, and PEEP for each of the patients. Furthermore, if one patient becomes disconnected from the circuit, Vt 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 Fio2 or to optimize Vt 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 Vt each patient receives is determined by the FGF to that patient’s circuit, providing complete independence in terms of Vt 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 three, four, or more subjects assuming 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 inline PEEP valves.

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. Second, 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 setup 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 ETT of either patient. Spirometry equipment is not freely available even in well-stocked hospitals, requiring Vrs to be assessed by portable devices or clinical signs such as chest excursions. As such, individualized monitoring for each circuit should be performed using stand-alone devices for Fio2, capnography, and airway pressure and flow, as available.

A pressure relief valve in the inspiratory limb of the secondary circuit is required for patient safety. Placing a one-way valve in the wrong direction in either limb of the patient circuit will increase the airway pressure leaving the pressure relief valve as the mitigation of last resort to prevent barotrauma. Our data were gathered without the relief valve because some of these valves began to leak gas at pressures below the set threshold pressure and interfered with our proof of concept measurements.

**CONCLUSIONS**

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.

---

**TABLE 4. Effect of Occlusion of the Inspiratory Limb of One Co-Ventilated Lung on the Remaining Lung With Disparate Compliances, Respiratory Rates, and Positive End-Expiratory Pressure Settings**

| Test Lung No. | Condition | Respiratory System Compliance (mL/cm H2O) | Respiratory Rate (/min) | Preobstruction Values | Postobstruction Values |
|---------------|-----------|------------------------------------------|-------------------------|-----------------------|-----------------------|
|               |           |                                          | Vt (mL) | PEEP (cm H2O) | Vt (mL) | PEEP (cm H2O) |
| 1             |           | 10                                       | 10       | 154 19           | 137 19 |
| 2             |           | 50                                       | 10       | 322 5            | 315 5  |
| 3             |           | 10                                       | 30       | 144 21           | 168 19 |
| 4             |           | 50                                       | 30       | 473 6            | 466 6  |

PEEP = positive end-expiratory pressure, Vt = tidal volume.

This table describes the summary results using one ventilator (Nellcor Puritan Bennet 840) in pressure control mode (60 mL/cm H2O) simulating obstruction of one patient’s circuit under differing values of compliance, Vt, and PEEP for the test lung. There were four experiments and results are presented for the lung that was not occluded.

---

**REFERENCES**

1. Neyman G, Irvin CB: A single ventilator for multiple simulated patients to meet disaster surge. *Acad Emerg Med* 2006; 13:1246–1249
2. Paladino L, Silverberg M, Charchalilieh JG, et al: Increasing ventilator surge capacity in disasters: Ventilation of four adult-human-sized...
sheep on a single ventilator with a modified circuit. Resuscitation 2008; 77:121–126

3. Beitler JR, Kallet R, Kacmarek R, et al: Ventilator sharing protocol: Dual-patient ventilation with a single mechanical ventilator for use during critical ventilator shortages. Columbia University College of Physicians & Surgeons and New York-Presbyterian Hospital. 2020. Available at: https://www.gnyha.org/wp-content/uploads/2020/03/Ventilator-Sharing-Protocol-Dual-Patient-Ventilation-with-a-Single-Mechanical-Ventilator-for-Use-during-Critical-Ventilator-Shortages.pdf. Accessed April 7, 2020

4. U.S. Food and Drug Administration: Appendix B. Authorized Ventilators, Ventilator Tubing Connectors, and Ventilator Accessories. 2020. Available at: https://www.fda.gov/media/136528/download. Accessed April 7, 2020

5. Society of Critical Care Medicine: Society of Critical Care Medicine, American Association for Respiratory Care, American Society of Anesthesiologists, Anesthesia Patient Safety Foundation, American Association of Critical-Care Nurses, and American College of Chest Physicians: Joint Statement on Multiple Patients Per Ventilator. 2020. Available at: https://www.sccm.org/getattachment/Disaster/Joint-Statement-on-Multiple-Patients-Per-Ventilator/Joint-Statement-Patients-Single-Ventilator.pdf?lang=en-US. Accessed April 7, 2020

6. Sommer DD, Fisher JA, Ramcharan V, et al: Improvised automatic lung ventilation for unanticipated emergencies. Crit Care Med 1994; 22:705–709

7. Branson RD, Blakeman TC, Robinson BR, et al: Use of a single ventilator to support 4 patients: Laboratory evaluation of a limited concept. Respir Care 2012; 57:399–403