



Ventilator Sharing during an Acute Shortage Caused by the COVID-19 Pandemic

To the Editor:

Coronavirus disease (COVID-19) is a rapidly expanding global pandemic. In March 2020, models forecasted imminent exhaustion of regional ventilator supply in New York (1). In response, we developed a novel ventilator sharing strategy to support two patients simultaneously with one ventilator. This report details our initial ventilator sharing experience among patients with COVID-19–associated acute respiratory distress syndrome (ARDS).

Methods

Ventilator sharing commenced as a public health preparedness initiative approved by the hospital leadership and ethics committee and by New York State (2). The clinical protocol and detailed methods are provided in the online supplement and <https://protocols.nyp.org>.

Patient selection. Respiratory physiology, infectious status, and clinical stability were evaluated to identify compatible patient pairs using prespecified criteria (Table 1). The protocol prioritized minimizing between-patient difference in driving pressure given the importance of protective tidal ventilation in ARDS (3).

In eligible patient pairs, deep sedation and neuromuscular blockade were initiated. Ventilators were set to pressure control with the initial driving pressure and inspiratory time adjusted to maintain each patient's baseline V_T . Then, driving pressure, inspiratory time, respiratory rate, and positive end-expiratory pressure (PEEP) were adjusted per protocol (*see* the online supplement), typically using the average value between patients unless otherwise indicated, to achieve identical settings for both patients. Inspired oxygen was adjusted as needed to maintain SaO_2 of 95% or higher. Thereafter, a safety check confirmed that V_T , minute volume, auto-PEEP, and arterial blood gas results remained within acceptable ranges. After demonstrating tolerance to identical settings on separate ventilators, patients were transitioned to a shared ventilator with the same settings.

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Circuit configuration. Circuit configuration safety features included redundant antimicrobial filters and patient-specific monitoring of V_T , airway pressure, and capnography (*see* the online supplement). Proper dual-circuit functioning was confirmed with test lungs before transitioning patients.

Patient management. Neuromuscular blockade and the pressure control mode were used during ventilator sharing to prevent respiratory effort or mechanical changes in one patient from affecting the other. Additional patient care considerations were followed per protocol. Patient care was directed by the patients' usual clinical team with support and assistance as needed from the ventilator sharing consult. The consult consisted of either of two intensivists (J.R.B. or A.M.M.) intimately familiar with the protocol, who alternated around-the-clock call whenever patients were on a shared ventilator. Ventilator sharing was predetermined not to exceed 2 days unless ventilator supply was exhausted.

Statistical analysis. Data were recorded during and for 48 hours before and after ventilator sharing. Time-series plots were created in SAS v9.4 (SAS Institute) without imputing missing data.

Results

Six patients (three pairs) with ARDS from COVID-19 underwent ventilator sharing during 1 week in March 2020 (Table 2).

Across patients, median V_T and pH were 5.7 ml/kg predicted body weight (interquartile range, 5.1–6.7) and 7.33 (interquartile range, 7.29–7.38) during ventilator sharing versus 6.0 ml/kg predicted body weight (interquartile range, 5.6–6.6) and 7.39 (interquartile range, 7.30–7.43) in the 48 hours before and after sharing (Figure 1 and Table E1 in the online supplement).

All patients tolerated the prescribed 2-day sharing period without adverse events and subsequently survived to hospital discharge. Video E1 presents circuit configuration and monitoring of two patients undergoing ventilator sharing. Lessons learned for each patient pair are as follows.

First pair. Patients shared an anesthesia machine using the pressure control mode of ventilation. Use of an anesthesia machine introduced several challenges.

Several staff lacked experience with anesthesia machines.

The CO_2 absorbent exhausted rapidly with two febrile patients with ARDS and was changed multiple times daily. Water produced from the absorbent's chemical reaction created excess circuit humidity that quickly saturated the heat and moisture exchanging filter, increasing circuit resistance and requiring the heat and moisture exchanging filter be changed every 8–12 hours.

The patients' combined minute volume (>20 L/min) exceeded the allowable range of alarm limits on the anesthesia machine. Audible alarms were notably subtler than on traditional ICU ventilators. Patient-specific respiratory monitors with alarms mitigated these issues.

The anesthesia machine's bulk and configuration necessitated circuit extension tubing, whose high compliance complicated ventilator titration.

Second pair. Patients shared a full-feature ICU ventilator using the pressure control mode of ventilation. Patient 2a was intubated

Table 1. Recommended Initial Patient Compatibility Criteria

Parameter	Acceptable Limit in Either Patient	Acceptable Difference between Patients (Patient A – Patient B)
Anticipated time needing invasive ventilation, h	72 or higher	—
V_T , ml/kg PBW	4–8	—
Driving pressure (ΔP = plateau pressure – PEEP), cm H_2O	5–16	0–6*
Respiratory rate, breaths/min	12–30	0–8
PEEP, cm H_2O	5–18	0–5
$F_{I_{O_2}}$, %	21–60	—
pH	7.30 or higher	—
Oxygen saturation, %	92–100	—
Ventilator titration	No recent major changes as judged clinically	—
Neuromuscular blockade	No contraindication to initiation if not already receiving	—
Respiratory infectious status	Both patients have same respiratory pathogen	None
Asthma or COPD	No severe baseline disease nor current exacerbation	—
Hemodynamic stability	No rapid vasopressor increase	—

Definition of abbreviations: COPD = chronic obstructive pulmonary disease; PBW = predicted body weight; PEEP = positive end-expiratory pressure. If patients do not meet all criteria, pairing them on a single ventilator is not recommended. Further details are provided in the full protocol (see the online supplement). PBW denotes predicted body weight in kg, calculated for males as $PBW = 50 + 2.3 [\text{height (inches)} - 60]$ and for females as $PBW = 45.5 + 2.3 [\text{height (inches)} - 60]$.

Acceptable differences for between-patient parameters were specified only for driving pressure, respiratory rate, PEEP, and respiratory infectious status. *Between-patient difference in driving pressure is the most important parameter to minimize in assessing potential compatibility of two patients.

16 hours before initiating ventilator sharing and exhibited overt, dyssynchronous active expiratory effort during screening, causing overestimation of subsequent mechanical support needs. Compatibility reevaluation after initiating neuromuscular blockade would have prevented this issue.

Third pair. Patients shared a full-feature ICU ventilator using the pressure control mode of ventilation without issue. A screening tool created in the electronic health record displayed key respiratory parameters for all invasively ventilated patients, facilitating rapid identification of compatible pairs.

With this experience, hospital leadership were confident ventilator sharing could be implemented at scale and adopted the protocol into the COVID-19 surge response plan.

Discussion

Prior ventilator splitting studies have included bench experiments with test lungs (4–6), animal models (7), and noninvasive ventilation in healthy volunteers (8). None have tested feasibility or safety in patients with lung injury.

Our protocol was designed with several patient safety features: patient compatibility criteria, restriction to two patients per ventilator, patient-specific monitoring, use of the pressure control mode of ventilation to ensure mechanical changes in one patient do not harm the other, use of medical-grade supplies, instructions for transitioning on and off the shared ventilator, management of divergent patient courses, and maintenance of an unoccupied rescue ventilator within each cluster of ventilator-sharing patients.

The greatest danger of ventilator sharing is wrongly equating the simplicity of its plumbing with ease of safe implementation. Patient selection and management require considerable expertise to ensure safety. Therefore, we recommend a regional referral model wherein ventilator sharing is restricted to expert centers, and patients and ventilators move throughout the region accordingly.

Alternative circuit configurations might add patient-specific PEEP or flow control valves to individualize support, or one-way valves to prohibit gas sharing. However, introducing new hardware to externally modify ventilator support during peak surge in patient volume—with non-ICU staff reassigned to ICU patient care in improvised clinical spaces (9)—is a setup for catastrophic human error. Even without human error, valve failure could result in asphyxiation. The ideal engineering solution is not the best clinical solution in this context.

Ventilator sharing does not obviate the need for more ventilators. Its greatest benefit may be when sufficient ventilators exist elsewhere and time is required to relocate ventilators or transfer patients. When resource and patient relocation are not options, ventilator sharing still may increase the number of patients supported and lives saved. However, it cannot double the number of supported patients. Some single-patient ventilators must be reserved for weaning and individualized support.

Limitations. Safety cannot be ascertained definitively from this small case series. Generalizability is untested, although our protocol's step-by-step instructions strengthen safety and reproducibility. This protocol requires neuromuscular blockade to ensure passive ventilation, which appears safe for 48 hours (10) but holds unclear risk if prolonged. The weaning strategy proposed in the protocol is untested but could become necessary if ventilator sharing is prolonged. Identification of compatible patient pairs is essential to safe implementation of ventilator sharing and is likeliest in high-volume centers with many candidate patients.

Conclusions. This report demonstrates feasibility of ventilator sharing for COVID-19-associated ARDS. Following a rigorous clinical protocol, carefully selected patient pairs receiving continuous neuromuscular blockade tolerated ventilator sharing for 2 days without adverse events. In acute

Table 2. Characteristics of Patients Undergoing Ventilator Sharing

Characteristic	Patient 1A	Patient 1B	Patient 2A	Patient 2B	Patient 3A	Patient 3B
Age, yr	62	74	58	73	43	59
Sex	Female	Male	Female	Female	Male	Male
Height, cm	162.6	182.9	157.5	175.0	165.1	190.5
Weight, kg	68.0	98.9	122.5	85.0	80.0	105.9
Body mass index, kg/m ²	25.7	29.6	49.4	27.8	29.3	29.2
Predicted body weight, kg	54.8	77.8	50.1	66.1	61.6	84.7
Vasopressor-dependent shock before sharing	Yes	Yes	Yes	Yes	Yes	Yes
Modified SOFA score before sharing*	10	10	12	13	10	11
Days hospitalized before intubation	1.0	3.1	1.1	1.0	1.0	6.1
Days intubated before ventilator sharing	5.6	2.5	0.7	7.9	1.8	3.6
Respiratory parameters prior to matching Ventilator mode	Volume control	Volume control	Volume control	Volume control	Volume-targeted pressure control	Volume-targeted pressure control
V _T , ml (ml/kg PBW)	330 (6.0)	480 (6.2)	400 (8.0)	490 (7.4)	375 (6.1)	370 (4.4)
Driving pressure, cm H ₂ O	14	16	24	22	19	20
Peak inspiratory pressure, cm H ₂ O	31	25	30	34	37	30
Plateau pressure, cm H ₂ O	28	24	34	32	31	30
Respiratory rate, breaths/min	26	19	24	25	26	28
PEEP, cm H ₂ O	14	8	10	10	12	10
F _I O ₂	0.5	0.6	0.7	0.5	0.3	0.6
Respiratory system compliance, ml/cm H ₂ O (ml/kg PBW/cm H ₂ O)	24 (0.43)	30 (0.39)	17 (0.33)	22 (0.34)	20 (0.32)	19 (0.22)
Minute volume, L/min	8.6	9.1	9.6	12.3	9.8	10.4
PaO ₂ /F _I O ₂ [†]	148	152	76	110	180	266
Duration of sharing, h		48.25		47.5		47.0
Time from start of ventilator sharing to last follow-up, d	36	56	39	33	42	55
Status at last follow-up	Discharged to SAR, nocturnal CPAP with no daytime support	Discharged to SAR, free from ventilator support	Discharged to SAR, free from ventilator support	Discharged to LTAC, nocturnal PSV with no daytime support	Discharged home, free from ventilator support	Discharged to SAR, free from ventilator support

Definition of abbreviations: CPAP = continuous positive airway pressure; LTAC = long-term acute care hospital; PBW = predicted body weight; PEEP = positive end-expiratory pressure; PSV = pressure support ventilation; SAR = subacute rehabilitation hospital; SOFA = sequential organ failure assessment.

*The original SOFA does not consider phenylephrine or vasopressin in the cardiovascular subscore. Patients receiving either of these vasopressors were assigned a SOFA-cardiovascular subscore of 3 unless other vasopressors warranted a higher score.

[†]Lowest value in 24 hours prior to ventilator sharing. All patients met diagnostic criteria for acute respiratory distress syndrome.

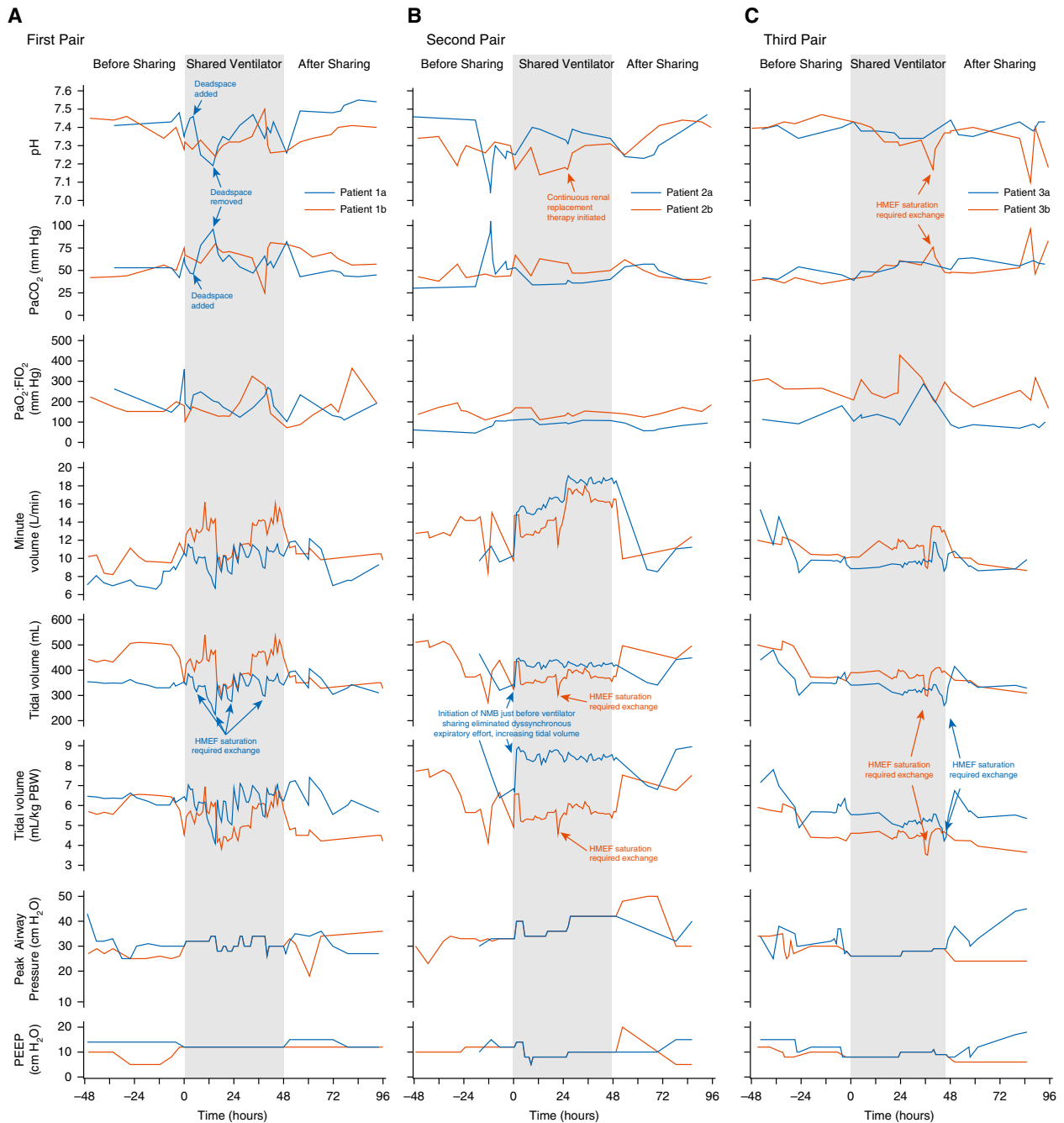


Figure 1. Clinical course of patients during ventilator sharing and for 48 hours preceding and afterward. (A) First pair. Patients shared a repurposed anesthesia machine. Approximately 4.5 hours after initiating ventilator sharing, patient 1a became alkalemic (pH 7.46), whereas patient 1b remained acidemic (pH 7.28). To treat alkalemia, deadspace tubing was added to the circuit of patient 1a, but resulting pH was lower than intended; with removal of this deadspace tubing, acidemia promptly improved. The HMEF had to be changed frequently for both patient circuits as CO₂ absorbent-related moisture buildup increased resistance, an effect most pronounced in patient 1a. (B) Second pair. Patients shared a full-feature ICU ventilator. Patient 2a's course illustrated the importance of ensuring steady-state ventilator requirements and reconfirming compatibility on neuromuscular blockade before initiating sharing. Patient 2a was intubated for 16 hours prior to ventilator sharing. During compatibility assessment, ventilator settings were matched and well tolerated but compatibility not reconfirmed after starting neuromuscular blockade in patient 2a; the patient exhibited overt, dysynchronous expiratory effort before paralysis, and eliminating respiratory muscle activity substantially increased V_T for a given driving pressure. Patient 2b was initiated on renal replacement therapy at Hour 28 for renal failure, which promptly increased pH. The patient's renal failure and plan for renal replacement predated ventilator sharing. (C) Third pair. Patients shared a full-feature ICU ventilator. V_T and acid-base balance were well controlled during ventilator sharing, reflecting cumulative experience and protocol refinement with incorporation of lessons learned. Patient 3b experienced a transient decrease in V_T and pH and increase in PaCO₂ around Hour 36 owing to HMEF oversaturation that promptly resolved with its exchange. HMEF = heat and moisture exchanging filter; NMB = neuromuscular blockade; PBW = predicted body weight; PEEP = positive end-expiratory pressure.

ventilator shortages, after exhausting alternatives, ventilator sharing is a reasonable stopgap to support potentially rescuable patients for at least 2 days in centers with appropriate expertise. This approach may be most useful when additional time is needed to relocate ventilators or patients to match supply with demand. The safety and utility of prolonged ventilator sharing, when ventilators or patients cannot be relocated, is unknown. ■

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Prone Positioning of Nonintubated Patients with COVID-19



To the Editor:

Epidemiological data on severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and the disease it causes, coronavirus

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