COMPUTATIONAL SIMULATION TO ASSESS PATIENT SAFETY OF UNCOMPENSATED COVID-19 TWO-PATIENT VENTILATOR SHARING USING THE PULSE PHYSIOLOGY ENGINE

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Abstract

Background
The COVID-19 pandemic is stretching medical resources internationally, including creating ventilator shortages that complicate clinical and ethical situations. The possibility of needing to ventilate multiple patients with a single ventilator raises patient health and safety concerns. This simulation study explores patient compatibility and ventilator settings during multi-patient ventilation without the use of flow compensating resistances.

Methods
A whole-body computational physiology model was used to simulate each patient on a ventilator. The primary model of a single patient with a dedicated ventilator was augmented to model two patients sharing a single ventilator. A range of ventilator settings and patient characteristics were simulated for paired patients. In addition to mechanical ventilation parameters, the full physiological simulation provides estimates of additional values for oxyhemoglobin saturation, arterial oxygen tension, and other patient parameters.

Findings
These simulations show patient outcome during multi-patient ventilation is most closely correlated to lung compliance, oxygenation index, oxygen saturation index, and endtidal carbon dioxide of individual patients. The simulated patient outcome metrics were satisfactory when the lung compliance difference between two patients was less than 12 cmH2O/mL, and the oxygen saturation index difference was less than 2 mmHg.

Interpretation
In resource-limited regions of the world, the COVID-19 pandemic will result in equipment shortages. While single-patient ventilation is preferable, if unavailable, these simulations provide a conceptual framework for clinical patient selection guidelines if ventilator sharing is the only available alternative.

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Introduction

The current COVID-19 pandemic has led to equipment shortages in Europe, the United States, and across the world. Inadequate availability of ventilators for patients in respiratory failure is especially challenging [1–3].

Ventilator sharing or splitting is one mitigation strategy that has been used in practice to rescue as many patients as possible when sufficient numbers of ventilators are not immediately available. Media reports from Las Vegas, Nevada, USA in October 2017 popularized this tactic employed during the surge of over 500 casualties after a mass shooting incident. Manual and improvised ventilation support was needed until stockpiled surge reserve ventilators could be delivered. Curiously, though news media reports are still readily discoverable, no citable healthcare literature has been found using extensive searches of PubMed, Google Scholar, and OVID.

The simplest approach for multiplex ventilation is to connect branched tubing without any compensating resistance in any branch for limiting flow to the most compliant patient(s). This is the only way shared ventilation is likely to be implemented rapidly with available tubing and adapters, without ready availability of flow compensating devices.

Only limited testing and clinical experience are available to expose the potential pitfalls of simplistic implementation. Branched breathing circuits to ventilate more than one patient with a single ventilator or compressed gas sources were published by Sommer et al. in 1994 [4], after contemplation of needs for ventilation of mass casualties from gas warfare at the time of the 1990-1 Gulf War [5]. A simpler concept published in 2006 with rudimentary simulation was employed at Las Vegas [6,7]. Chatburn et al. have studied ventilation of two breathing simulators using pressure control and volume control modes of ventilation for six pairs of simulated patients without compensating flow resistance. Carbon dioxide tensions were estimated and used to estimate pH for each modeled patient [8]. Hermann et al. have studied pressure and volume ventilation modes using a computational model of lung ventilation and by test lung experimental simulation [9].

Paladino et al. published a 12-hour proof-of-concept using a single ventilator for four healthy adult sheep, reporting some difficulties even with well-matched "patients" [10]. Letters in response to Paladino’s study raised concerns that the demonstration was not a sound foundation for translation to clinical use, especially for anticipated mass casualty scenarios producing a variety of lung pathophysiologies. They discussed anticipated issues including differing compliances, spontaneous breathing, dyssynchrony with the ventilator, expected shortages of pharmaceuticals and oxygen, monitors, and skilled personnel for vigilant management of patients on shared breathing circuits in a surge situation [5, 11].

Due to the perceived risks of having multiple patients per ventilator a consortium of North American professional societies issued a joint statement opposed to this practice, available from several internet sources [12]. The joint statement gives only slight acknowledgment to desperate triage situations whereby dedication of one ventilator exclusively to one patient may determine the demise of another if some means of ventilation cannot be provided. The enumerated considerations of the joint consensus statement are realistic and concerning. However, they abdicate the possibility that split ventilation could be safely and effectively implemented. The identified issues may be considered an agenda for further investigation.

Faced with mounting needs for ventilator support of COVID-19 patients and limited resources, FEMA and healthcare systems prepared clinical guidelines for ventilator sharing using pressure support mode, chemical paralysis, and vaguely stated "similar mechanical support needs" [13–15]. Potential risks are enumerated, including unintentional extubation of one patient, cross-contamination, and delayed observation of hypo- or hyper-ventilation. The US Department of Health and Human Services (HHS) issued a document containing a statement that the FDA would not object to split ventilation for the duration of the declared COVID-19 emergency when demand for invasive ventilation exceeds the supply of ventilators. Protocols from a Washington DC COVID-19 Taskforce (Babcock et al.) and the New York Presbyterian-Columbia collaboration (Beitler et al.) are included within the HHS document [16].

Simple branched-flow circuits for a ventilator do not incorporate flow compensation to limit excessive distribution of ventilation to the most compliant lungs. The Mount Sinai group empirically compensated for the maldistribution of ventilation by incorporating a needle valve to restrict breath flowing to the most compliant lungs. Initial simulation testing of shared ventilation using a single ventilator employed two high-fidelity lab manikins. Subsequently, two consented ICU patients were supported for one hour by a
single ventilator with a split breathing circuit. At another time, two other consented ICU patients were supported for an hour by one ventilator. Some of the assertions of the joint statement are addressed in an appendix [17]. Similar apparatus has been described by an on-line collaborative [18] and another pre-publication document from Yale [19]. Clarke et al. have reported using simple compression clamps on segments of tubing [20].

The joint statement and limited empirical information suggest a range of inadequately addressed issues. These provide opportunities for future conventional research and complementary opportunities for modeling and simulation. As a last resort means of providing ventilation, the necessary questions to be answered for the complex considerations of split breathing circuits powered by a single ventilator are what parameters provide "guard rails" for safe use.

Computational simulation provides an opportunity to quickly develop guidance over a wide range of possible clinical scenarios, without incurring patient risk. While empirical reports have been published [17], we have found only limited reports of empirical human simulation (with masks and hyperventilation) [21] and no computational simulation literature to inform multiple patient shared ventilation, nor specific definition of "similar mechanical support needs" [16]. Thus, it is clear that a method is needed to study and navigate this multi-parameter space and multiple scenarios in this complex system. We undertook a computational simulation of dual patient ventilation with a single ventilator using a computational whole-body simulation model to produce informed clinical parameters addressing noted assumptions and assertions. Use of whole-body physiological simulation exposes secondary effects that would not be apparent when modeling mechanics of ventilation alone.

The Pulse Physiology Engine (Kitware, Inc., Clifton Park, NY) open source software was previously designed and validated to model a single patient-ventilator pairing [22]. We modified and employed this model to simulate two or more patients sharing a single ventilator resource. This computational model permits rapid evaluation of a wide range of possible scenarios to educate clinicians about the potential risks for mismatched patients ventilated through uncompensated branched breathing circuits attached to a common ventilator. As a computational model without risk to patients, clinically untenable possibilities can be explored to determine guidance or "guard rails" to inform clinical practice, hopefully averting risky clinical practices and potentially poor outcomes.

Methods

Pulse Overview

Concurrent pressure controlled ventilation of two patients in a configuration without flow-compensating resistance is being modeled by computational simulation. The Pulse Physiology Engine (pulse.kitware.com) models are built on the pioneering work of Ty Smith [23], further developed by the Department of Defense as BioGears (W81XWH-13-2-0068), and finally forked, continually developed, and supported for diverging uses as Pulse. Pulse is comprised of lumped-parameter models, which use electrical circuit analogues (e.g., resistors and capacitors) to represent the behavior of physiological regions or systems of the human body [22]. Feedback mechanisms and interactions of systems are accomplished through circuit connections or scaling circuit elements [24]. These circuit models are then solved using transient circuit analysis. Substances can be circulated through the models using pharmacokinetic (PK) and pharmacodynamic (PD) models, which use the physiologic properties of the patient and the physicochemical properties of the drug in differential equations to represent drug diffusion and distribution in the body [25]. Disease and treatment models are designed with differential equations describing the effects of disease and treatment and then applied to the lumpedparameter models to affect the overall calculations. Thus, the Pulse Physiology Engine models patient physiology interacting with medical equipment. The Pulse engine has a rigorous validation standard driven by data from the literature, patient data, and our relationships with clinical experts in a number of medical fields. More details on the transient circuit analysis, substance transport, and validation process can be found in the supplemental data published on the Pulse website (https://pulse.kitware.com/_docs.html). For this study, the Pulse ventilator implementation has been improved. The Pulse lung models were also modified and extended to enable more than one patient interacting with a single ventilator.
Patient Model

Recent studies of laboratory-confirmed COVID-19 pneumonia patients that received invasive mechanical ventilation have shown the PaO$_2$/FiO$_2$ ratios were consistent with the Berlin criteria for moderate-to-severe ARDS [26, 27]. However, COVID-19 patients also present an atypical form of ARDS with dissociation between well-preserved lung mechanics (i.e., compliance) and unusually severe pulmonary shunt fraction with consequent hypoxemia [28, 29].

Based on these data, the existing Pulse ARDS pathophysiology model was used. Additionally, the patient resistance, compliance, alveolar surface area, and pulmonary shunt fraction can be modified individually or by specifying a patient disease "severity." The severity is defined between zero (no change from the healthy state), and one (life-threatening). Severity values of 0.3, 0.6, and 0.9 meet accepted criteria for mild, moderate, and severe ARDS, respectively, including PaO$_2$/FiO$_2$ and shunt fraction changes. To model COVID-19, the ARDS disease severity mappings that represent the combined effects of the reduction in alveolar surface area and increase in pulmonary shunt were used. The combined changes are defined here as the diffusion impairment factor (DIF). The DIF selectively hinders gas exchange and emulates hypoxemic respiratory failure.

Using Pulse’s whole-body modeling approach, the patient is administered a neuromuscular transmission blocker and intubated, as defined by current clinical guidelines [16]. The patient’s diseased steady state is achieved in combination with other features of the Pulse whole-body model.

Multi-patient Ventilator Model

The Pulse ventilator model was first developed and tested with single-patient simulations and has been validated through pure simulation and integration with physical systems [30]. For this study, the Pulse ventilator model was executed in Pressure Control Continuous Mandatory Ventilation (PC-CMV) mode, following existing multi-patient ventilation guidelines [16, 19]. A square driving pressure waveform was specified by user-defined Positive End Expiratory Pressure (PEEP), Peak Inspiratory Pressure (PIP), respiratory rate (RR), and Inspiratory: Expiratory (IE) ratio. The ventilator gas fractions, such as Fractional inspired oxygen (FiO$_2$), were also specified. The inspiratory, expiratory, and endotracheal tubes are included as part of the lumped-parameter circuit in Pulse. These comprise a closed-loop circuit and a branch for each patient and the ventilator for pneumatic and substance transport analysis. All tubing was estimated to be 3 feet long with a 22 mm inner diameter. The associated tubing resistance is negligible compared to the patient’s tracheobronchial resistance. One-way (check) valves are present to prevent backflow.

Previously, the Pulse engine represented a single patient and the associated equipment. To simulate a single ventilator connected simultaneously to two or more Pulse patients, required the creation of a new multi-patient ventilation engine. The new Pulse multi-patient engine simulates multiple patient physiology engines in lockstep to compute the effects of unequal, and potentially dynamic, differences in patient breathing mechanics when connected in parallel branched breathing circuits subject to a single pressure-mode ventilator. Figure 1 shows an overview of the multi-patient simulation environment.
Figure 1: *The approach for simulating multi-patient ventilation.* An entire system state is calculated every 2 ms. The Pulse dynamic circuit solver and transporter are leveraged to ensure sound physics-based results with conservation of energy and mass. Mechanistic interactions occur with all other Pulse physiological systems, most notably, the alveolar-capillary partial pressure gradient diffusion gas exchange with the cardiovascular system.

Multi-patient Ventilation Simulation Design

COVID-19 respiratory mechanics parameters were gleaned from the available literature. An initial in silico investigation (computational simulation) used a sparse sampling of the combined mechanical ventilator and COVID-19 patient parameter space to understand patient outcome patterns. These simulations combined various ventilator PEEP settings with patient compliance and disease severity values. Tidal Volume (TV) and arterial partial pressure of oxygen (PaO₂) were evaluated. This simulation was implemented as a two-step process: 1) patients were simulated with various levels of disease states connected to an individual ventilator with increasing FiO₂ values until a homeostatic point (pulse-oximetric oxygen saturation, SpO₂ > 89%) was reached; then 2) patients were paired in three separate simulations using each patient’s individual ventilator settings and average values for the two paired patients. Hyperoxia was considered an undesirable, exclusionary outcome in this initial model.

A scoring methodology was developed to analyze the simulation results and to identify safe clinical "guard rails" for patient pairing and specifying ventilator settings. The patient pair outcome was scored as follows:

- **Positive (green)**
  - TV (mL/kg) - both patients between 5.5 and 6.5
  - SpO₂ (%) - both patients above 89
  - PaO₂ (mmHg) - both patients below 150

- **Less Positive (yellow)**
  - TV (mL/kg) - both patients between 4.5 and 7.5
  - SpO₂ (%) - both patients above 89
  - PaO₂ (mmHg) - both patients between 150 and 200 (hyperoxemia)

- **Negative (red)**
  - TV (mL/kg) - either patient below 4.5 (underinflation) or above 7.5 (overinflation)
– SpO₂ (%) - either patient under 89 (severe hypoxia)
– PaO₂ (mmHg) - either patient above 200 (oxygen toxicity)

If all parameters are in the target range, the result is scored green. If a patient has a tidal volume or SpO₂ parameter in the yellow or red criteria, the patient is scored in the lowestscoring category. Only in the initial analysis was hyperoxia scored yellow or red.

The initial results informed a more thoughtful discretization of the parameter space in the full simulation study. The initial experiments revealed that the PIP and FiO₂ should be specified as values providing the best chance of positive outcomes for both patients, as opposed to using average values or those of a single patient. Therefore, the ideal drive pressure (PIP - PEEP) for each pair of patients was directly calculated based on a target tidal volume (6 mL/kg) and known average static respiratory compliance (C_stat). The FiO₂ was determined through simulation by finding the lowest value between 0.21 and 1.0 that stabilized both patients to a SpO₂ of at least 89%. In this final analysis, hyperoxia (oxygen toxicity risk) alone was not scored yellow or red, being considered a likely acceptable expression of good or improving gas exchange.

All possible combinations of patient parameters required evaluation of 12,642 unique patient and ventilator combinations defined by the following parameter space:

- Mechanical ventilator (one per simulation):
  – Respiratory rate (bpm) - Fixed at 20
  – I:E ratio - Fixed at 1:2
  – PEEP (cmH₂O) - range of 10 to 20 in increments of 5
  – PIP (cmH₂O) - Derived from 6 mL/kg given PEEP
  – FiO₂ - Derived through simulation for both patients’ SpO₂ > 90% (if possible)

- Patient (two per simulation):
  – Total respiratory resistance (cmH₂O-s/L) - Fixed at 5
  – Total respiratory static compliance (mL/cmH₂O) - a range of 10 to 50 in increments of 1
  – DIF (severity 0 to 1) – 0.3 to 0.9 in increment of 0.1

Two equal-sized 70 kg patients are modeled. This should not limit the applicability of these results because pressure mode ventilation does not enforce delivery of a set volume, which could be injurious. Only a single respiratory resistance per patient branch was modeled because clinical variations of airway resistance have not been found to be a prominent characteristic of COVID-19 ARDS [26,28].

Results

Patient Simulation

This Pulse COVID-19 model is an extension of the existing ARDS methodology that has been validated with referenced empirical data and trends [31]. Scenarios with the Pulse standard, properly ventilated ARDS patient shows good agreement with expected outcomes [32,33]: severities matching mild, moderate, and severe cases resulting in PaO₂/FiO₂ of 340, 130, and 50 mmHg, respectively, and shunt fractions of 8%, 27%, and 59%, respectively. Validated ARDS and mechanical ventilator models, with the added ability to specify the patient’s respiratory compliance, allows for reasonable COVID-19 pathophysiology simulations.

Each of the 287 unique COVID-19 patients created (based on DIF and compliance combinations) for the full study were simulated as single patients with their own ventilators to ensure they were capable of achieving 89% SpO₂ (green outcome) at maximum FiO₂. Those patients that were unable to meet this criterion were excluded from further multi-patient ventilation analysis to prevent skewing resulting guidelines. Table 1 shows that 71% of patients with 0.8 DIF and 100% of patients with 0.9 DIF were disqualified for shared ventilator simulation.
Multi-patient Ventilation Simulation

Results of an example paired patient simulation are shown in Figure 2. The TV is significantly different because of the $C_{\text{stat}}$ mismatch (plot a). The $\text{PaO}_2$ values and response to oxygenation differ largely from the DIF (plot b). Because $\text{CO}_2$ transits tissue much more readily than oxygen, the DIF affects $\text{O}_2$ more severely than $\text{CO}_2$ (plot b).

Parameter differences between patient pairs were evaluated using the scoring methodology described previously. The absolute value of the difference of specific parameters from patient one and patient two was analyzed using a one-way analysis of variance (ANOVA) to determine relative correlations to outcomes. An F-test was used to statistically test the equality of means, with larger $\eta^2$ values denoting higher correlation, as shown in Table 1. Five parameters were found to be most correlated to outcomes: $C_{\text{stat}}$, End-tidal $\text{CO}_2$ (Et$\text{CO}_2$), Alveolar-arterial (A-a) gradient, oxygen saturation index (OSI), and oxygen index (OI). Three of these parameters can be measured non-invasively on patients: $C_{\text{stat}}$, Et$\text{CO}_2$, and OSI.
Table 1: The results of an outcome correlation statistical analysis. Parameters are differences (Δ) between co-ventilated patients. Larger $\eta^2$ values denote greater correlation.

| Parameter                          | Abbreviation / Equation                  | Outcome Correlation ($\eta^2$) |
|------------------------------------|------------------------------------------|--------------------------------|
| Respiratory Compliance*            | $\Delta C_{stat}$                        | 0.46                           |
| End Tidal Carbon Dioxide*          | $\Delta EtCO_2$                          | 0.46                           |
| Alveolar-arterial Gradient         | $\Delta A-a \text{ Gradient} = \Delta(PA_2 - PaO_2)$ | 0.18                           |
| Oxygen Saturation Index*           | $\Delta OSI = \Delta(FiO_2 * MAP * 100/SpO_2)$ | 0.11                           |
| Oxygen Index                       | $\Delta OI = \Delta(FiO_2 * MAP * 100/PaO_2)$ | 0.11                           |
| P/F Ratio                          | $\Delta P/F \text{ Ratio} = \Delta(PaO_2/FiO_2)$ | 0.08                           |
| Diffusion Impairment Factor*       | $\Delta DIF$                             | 0.02                           |
| Mean Airway Pressure*              | $\Delta MAP$                             | 0.02                           |
| S/F Ratio*                         | $\Delta S/F \text{ Ratio} = \Delta(SpO_2/FiO_2)$ | 0.02                           |

*Denotes non-invasive, + denotes a model parameter

Parameter independence was assessed using the Pearson product-moment correlation coefficient (PPMCC) method. The results in Figure 3 show that two of the four correlated parameters are both non-invasive and independent, $C_{stat}$, and OSI. Therefore, these two parameters were plotted against simulated clinical outcomes in Figure 4.

Figure 3: The selected parameters for investigation are compared with each other to determine their dependence. The PPMCC method is used to calculate a value between -1 (inversely correlated) and 1 (correlated). Those with low correction (close to 0) are more independent of each other and are therefore the best candidates for informed decision-making.
Figure 4: Comparison of multi-patient ventilation simulated outcomes due to TV (plot a) and PaO_2 (plot b) outcome bounds. Each graphical dash is a full simulation. Included are univariate histogram plots for each axis using kernel density estimation to represent the distribution of all three outcomes described in two dimensions. The compliance (abscissa) has discrete values due to the chosen patient parameter setting methodology and fluid mechanics. The OSI (ordinate) is dependent on all external settings, along with the complex interactions of internal mechanistic models. Note that while the OSI has units of mmHg (because it is a ratio of pressure divided by saturation), the interpretation is like the unitless OI value.

While respiratory compliance is a direct indicator of outcome based on lung recruitment, Figure 5 shows that OSI is an important and effective measure of overall diffusion impairment.
Figure 5: Distribution of all simulated patient’s OSI grouped by the seven DIF settings used from mild to severe. The OSI increases with DIF and is, therefore, a useful non-invasive clinical measurement of hypoxemic respiratory failure. The OSI increases with diffusion impairment because the SpO$_2$ which plateaus at 100, is a proportionately larger fraction of PaO$_2$ as diffusion impairment and shunt make PaO$_2$ less than expected for a given FiO$_2$.

The combined outcomes as a function of the patient parameter mismatches are used to generate a complete decision matrix in Figure 6. The simulation results show that patients with similar respiratory compliances and comparable OSI are likely to have good outcomes when paired for multi-patient ventilation.

Figure 6: The simulations from Figure 5 were holistically taken into account to get a complete decision matrix. Outcomes were assigned a normalized value of green = 1, yellow = 0.5, and red = 0 to encode a z-axis as colors or color gradient. The resulting three-dimensional scatter plot (plot a) was used to produce an interpolated surface using the first-order bivariate B-spline method (plot b).
An interactive version of the model is available via a Jupyter notebook in the Pulse repository (https://gitlab.kitware.com/physiology/jupyter).

Discussion

The results demonstrate the ideal parameters for determining clinical guidance for multipatient ventilation are lung compliance and OSI, as they are noninvasively measured and highly correlated to outcomes. OSI has also been shown to be a significant indicator of clinical outcomes for ARDS [34]. Our simulations show that a difference up to approximately 12 mL/cmH2O in lung compliance and an OSI difference of less than two mmHg anticipate satisfactory patient outcomes. This information may inform clinical guidelines when pairing patients on a single ventilator. A limitation of this conclusion is that this is a pure simulation study, and we do not have correlated patient data. Our future work includes comparing our computational simulations to physical experiments using the simple lung simulators with selectable settings for resistance, compliance, and effects of negative inspiratory pressure patient-initiated breath triggers [IngMar Medical, QuickLung® Adult Precision Test Lung with QuickTrigger, part number 15 00 100, www.ingmarmed.com].

Implementation of split breathing circuits without compensating resistances was the model addressed in the joint statement by professional societies recommending against this practice [12]. Various means have been employed empirically to limit flow to the most compliant lungs [17–20]. Modeling flow restriction adds model parameters, greatly increasing the number of simulations needed. For those locales with the most rudimentary resources, flow restriction devices may not be possible. Future work will investigate sharing ventilators by more than two patients, and the use of flow restrictors in circuit branches to facilitate separate control of tidal volume delivered to individual patients during multi-patient ventilation.

If there is an adequate supply of ventilators available, individual ventilators are preferable and optimal [5, 7, 11]. Numerous efforts to produce quantities of individual ventilators have been kindled by an anticipated surge of patients needing ventilator support. There has been a surge of creative projects, yet there are gaps to be bridged before mass production could be a reality [35]. The FDA has issued Emergency Use Authorizations (EUA) for some innovative ventilators not from usual medical equipment vendors [36]. Whether a surge of supply will be needed or available remains to be seen.

However, even with numerous creative projects creating basic ventilators from readily available components, there may not be enough locally available in a surge emergency. The primary default is manual ventilation, usually with bag-valve-mask (BVM) devices. Prolonged manual ventilation is difficult to maintain. Split breathing circuits can be quickly assembled from available breathing circuit components for a transition to mechanical ventilation. Ventilation equipment not usually employed for critical care may also be pressed into service in a crisis, e.g., CPAP and BiPAP as ventilators, anesthesia machines, and high-flow non-invasive ventilation devices.

Multi-patient ventilation may be the only available option for poorly resourced regions. Manufacturing of single patient ventilators, however primitive, is an unlikely prospect for countries with limited resources. A personal communication from a Sudanese engineer interested in producing ventilators in-country stated that the entire country has only 80 ventilators and very limited materiel or manufacturing resources. Whatever can be done with resources already present in the country is their only available option (Conversation with MS, 28 Mar 2020, SMP). Similar limitations also apply for very populous countries, such as India, though they may be able to rally more resources for high throughput manufacturing. For these critical scenarios, we intend that these simulations could inform clinical guidelines for patient pairing on a single ventilator.

Under extreme circumstances, and in resource-challenged regions limited by the availability of an adequate number of ventilators, multi-patient ventilation is a potentially viable option and can significantly increase the capacity to care for critically ill patients in surge scenarios. Our computational simulation study provides ranges of basic physiological parameters that could be used in patient selection for future studies evaluating multi-patient ventilation. After further validation with physical models, our simulation could also inform clinicians for pairing patients on a single ventilator.

The simulation software, data, and a UI for exploring the simulations is available open-source at the Kitware GitLab site (https://gitlab.kitware.com/physiology). For more details, see the supplement.
Research in Context

Evidence before this study

If numbers of patients requiring mechanical ventilation exceed the number of available ventilators in a surge, shared branched ventilator circuits have been proposed for sharing one ventilator by multiple patients. Only rudimentary laboratory or clinical studies have been reported. Testing over expected ranges of lung-chest wall compliance has not been found. Few clinical experiences of mechanical ventilation parameters employed for COVID-19 patients have been reported.

Added value of this study

The number of possible combinations of ventilation and physiological parameters is very large. Time and resource constraints do not permit conventional research. Computational simulation provides rapid sensitivity evaluation of several factors over a wide range of hypothetical ventilation conditions. Envelopes of evaluated parameters may provide reasonably estimated safety boundaries for clinicians compelled in an emergency surge to employ a poorly characterized practice. A previously well-vetted computational model for ventilation of a single patient by a dedicated ventilator has been modified to model the sharing of a single ventilator by two or more patients. Only pairings of two equally sized 70 kg patients are modeled in this report. These simulations provide estimates of effects on ventilation and blood oxygenation by clinically measurable values using conceivable mismatched patient lung compliance and oxygenation (diffusion and shunt).

Implications of all the available evidence

These estimates are for pressure mode ventilation using a single ventilator shared by branched breathing apparatus for paired patients. Individual patient flow restriction to compensate for compliance mismatch is not considered. Reasonable though arbitrary bounds of acceptable parameters may guide clinicians when determining pairings of patients with different physiological characteristics. Further laboratory testing and clinical experience will be needed to determine the validity or utility of these assessments. Different simulations will be needed for flow-compensated branches, more than two patients, and unmatched body habitus.
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