Splitting one ventilator for multiple patients – a technical assessment

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Abstract

Due to the recent coronavirus outbreak, many efforts and innovative solutions have surfaced to deal with the possible shortage of ventilators upon catastrophic surges of patients. One solution involves splitting one ventilator to treat multiple patients and is in principle easy to implement, but there are obvious risks and little is known on how the technique would work on patients with ARDS from Covid-19. Previous studies have shown that multiple test lungs of equal characteristics can be successfully ventilated from one machine, but that large variations in tidal volume delivery occurs when lungs with different compliance are connected. In contribution to the discussion of the feasibility of the technique, a technical assessment was done including experiments expanding on the previous studies with different ventilator setting and lung characteristics. Using two test lungs connected to a ventilator, the tidal volumes and pressures into both lungs were measured for different combinations of lung compliance, airway resistances, modes of ventilation, inspiratory and end-expiratory pressure levels. We found large discrepancies in delivered tidal volumes for paired test lungs with compliance differences, little influence from differences in airway resistances, and that higher PEEP settings could strongly influence the tidal volume balance between the test lungs. The most balanced, although far from ideal, delivery of tidal volumes for the test lungs with different compliance was measured using pressure-controlled ventilation with a maximum inspiratory pressure of 30 mbar and a PEEP at 6 or 10 mbar. From this study and from a technical point of view, we were not able to identify reliable settings, adjustments or any simple measures to overcome the hazards of the technique.

Introduction

During catastrophes with a surge of patients needing ventilatory support exceeding the number of available ventilators, a solution has been proposed for connecting multiple patients to the same ventilator. Neyman and Babcock Irvin introduced this concept in 2006, which is described below. The solution is very simple to implement, requiring only three T-tubes, adapters and extra tubes for each patient. With the recent coronavirus pandemic, interest in the solution has quickly spread globally, but little is known on how the solution works in reality, in particular for the treatment of ARDS from the coronavirus.

Description of the solution

The Neyman and Babcock Irvin solution involves connecting four patients to one ventilator by four sets of tubes connected to the ventilator using two T-way splitters as shown in figure 1, one for the inspiratory and another for the expiratory limb. The splitter is made of three T-tubes and connection
adapters connected as shown in figure 1b. Other types of splitters such as Y-connectors should work equally.

Figure 1. Example of a connection of three T-tubes and adapters to make a splitter for four patients connected to the inspiratory and expiratory limb of one ventilator.

The solution is explained in video several places online, including one video by Babcock Irvin (www.youtube.com/watch?v=uClq978oohY)

Relevant tests to date
Neyman and Irvin 2006 did a simulation study of the method on four equal test-lungs (Puritan-Bennet) that were ventilated for about six hours using pressure-controlled ventilation (peak pressure of 25 cmH20) followed by another six hours of volume-controlled ventilation (2000 mL tidal volume). The positive end-expiratory pressure (PEEP) was set to 0 cm H2O, the respiratory rate to 16 breaths/min for
both modes, and the circuit was inspected approximately every 20 minutes visually checking the test lungs and recording the ventilator display. A quite even distribution in tidal volume between the four lungs was recorded with 471±22 mL for pressure control and 507±1 mL for volume control. The authors indicate further studies for testing of efficacy and safety, but suggest a significant potential for the expanded use of a single ventilator during cases of disaster surge involving multiple casualties with respiratory failure.

Paladino et al. 2008 went further and tested the principle in an animal study on four 70 kg sheep ventilated for 12 hours. The method was similar to Neyman and Babcock Irvin, but with microbial filters added on each expiratory limb. Arterial pH, pCO₂, pO₂, heart rate and blood pressure was monitored during the course of the experiment. Although there were issues with CO₂ retention and poor oxygenation due to positioning, and a case of hypoxia due to adverse reaction to induction agents, the authors report successful oxygenation and ventilation of all animals for 12 h while keeping them hemodynamically stable.

Branson et al. 2012 did a study similar to Neyman and Babcock Irvin, but with test lungs having variable airway resistance and compliance (the inverse of stiffness). In this way, they could study how the method would work if patients with different lung characteristics would be connected to the same ventilator. They found that the ventilation was distributed quite evenly for lungs with equal resistance and compliance, but found large differences in the ventilation between lungs (from 257 to 621 mL tidal volume) having different compliance. The authors recommend avoiding the use of this method, given the potential hazardous and untoward complications.

The only study done on humans to our knowledge is a test on two awake volunteers ventilated through facemasks for ten minutes, connected to the same ventilator (Draeger Evita XL) by Y-connectors splitting the inspiratory and expiratory limbs (Smith and Brown 2009). Ventilation was given by pressure-control with an inspiratory pressure of 30 cm H₂O, PEEP at 2 cm H₂O, 18 breaths/min while inspiratory and endtidal CO₂ was monitored at the masks. After ten minutes, both subjects’ endtidal CO₂ were acceptable (4.7 and 5.7 kPa) and well tolerated.

The technique is known to have been used for two patients sharing one ventilator in an emergency after a shooting incident in Las Vegas, USA (Emergency Physicians Monthly).

Table 1. Published results on using one ventilator for multiple patients

| Study            | Model                                    | Reported results                                      |
|------------------|------------------------------------------|-------------------------------------------------------|
| Neyman and Babcock Irvin 2006 | 4 equal test lungs ventilated approximately 6 hours | Evenly distributed ventilation among all test lungs     |
| Paladino et al. 2008     | 4 sheep ventilated for 12 hours          | Sufficient ventilation, oxygenation and hemodynamic stability throughout the experiment |
| Smith and Brown 2009     | 2 human volunteers ventilated for 10 minutes | Acceptable CO₂ levels after 10 minutes of ventilation |
| Branson et al. 2012     | 4 test lungs with different combinations of resistance and compliance | Even distribution of ventilation for equal lungs, large differences in ventilation between lungs with different compliance |
Summary and discussion of previous studies

The combined data from relevant studies is scarce and not very relevant to ARDS, making it difficult to draw any conclusion on the suitability of the method (see table 1 for an overview). The method has been discussed and faced criticism among expert, cautioning against usage.

These tests have shown that the technique may work technically under given circumstances, but with the lack of relevant tests and the potential hazards, the method has received strong criticism since first published. Branson published comments on both the studies from Neyman and Babcock Irvin and the Paladino study in letters to the Editors in Acad. Em. Med and Resuscitation (Branson 2006 and 2008), pointing to weaknesses of the studies and raising concerns on patient safety. Concerns are raised with the animal study (Paladino et al. 2008) is for being too optimistic with the animals having episodes of hypoxia and hypercapnia despite having no deliberate pulmonary pathology, and less relevant as the animals had well functioning lungs.

The method has been commented by an expert group on critical care (Lewis et al. 2007):

“Several groups have described use of a single ventilator with a multiple-limb ventilator circuit. While at first glance this strategy is appealing, the research to date has demonstrated only that similar test lungs and pharmacologically paralyzed sheep with normal lungs can be ventilated by this approach. Perhaps this strategy would have utility for ventilating patients with normal lungs (eg, isolated traumatic brain injury) and thereby free additional ventilators for patients with high resistance or low compliance. Extrapolation to EMCC would require pharmacologically paralyzed patients who remain matched for minute ventilation requirements, dynamic airflow resistance, and compliance throughout the duration of ventilation; however, these parameters are likely to vary during the duration of mechanical ventilation, and may even change over a period of minutes (eg, secretions causing increased airflow obstruction)”

Recently, protocols have been developed for implementation of the method around the world, and at the same time, the Society of Critical Care Medicine has published a Consensus Statement on Multiple Patients Per Ventilator (March 26 2020), advising against the use of the technique (www.sccm.org/Disaster/Joint-Statement-on-Multiple-Patients-Per-Ventilato).

Due to the lack of data on the feasibility of the technique, we conducted a study with a series of tests in our department, extending the relevant cases of lung characteristics and ventilator settings tested previously. The aim of this study was to learn more about the feasibility and issues with the technique and provide more data from relevant experiments to support the evaluation of the concept from a technical standpoint.

Methods

Two test lungs (Imtmedical Smartlung Adult) were connected to one ventilator (Avalon Medical Leon Plus anesthetic machine) using T-connectors as shown in figure 3. One of the test lungs (Lung A) had a constant compliance specified to be 25 mL/mbar, while the other test lung could be set to four levels of compliance (10, 15, 20 and 30 mL/mbar). The true compliance of the test lungs were measured by the ventilator to be 28 mL/mbar for Lung A and 7, 14, 20 and 29 mL/mbar for the levels of Lung B. Both test
lungs has adjustable airway resistance at the connection into the lung, possible to adjust to 5, 20, 50 and 200 mbar/L/s. For monitoring of tidal volumes and pressures into the lungs, a Heinen Löwenstein flow and pressure analyzer was connected between each lung and the assigned inspiratory and expiratory tubes.

The aim was to investigate how the distribution in ventilation between the two lungs depends on differences in compliance, and how this dependency relates to the airway resistance, mode of ventilation (pressure or volume control), levels of maximum inspiratory pressure (Pmax) and the extrinsic PEEP. Table 2 shows all settings used in the tests. For volume-controlled ventilation, we used a tidal volume of 900 mL to obtain 450 mL in both lungs upon balanced ventilation. An earlier test with the same setup showed that the distribution between the two test lungs was independent of the tidal volume setting (from 900 to 1500 mL), hence we used only one setting at 900 mL for the volume controlled tests. As default, a PEEP of 6 mbar was used unless mentioned otherwise.

Table 2. Settings for the ventilator and test lungs used in the study.

| Setting                        | Levels                  |
|-------------------------------|-------------------------|
| Compliance Lung A             | 28 mL/mbar              |
| Compliance Lung B             | 29 mL/mbar 20 mL/mbar   |
|                               | 14 mL/mbar 7 mL/mbar    |
| Airway resistance             | 5 mbar/L/s 20 mbar/L/s  |
|                               | 50 mbar/L/s             |
| Ventilator mode               | Volume controlled       |
|                               | Pressure controlled     |
| Pressure limitation (volume-control) | 30 mbar      |
| Max inspiratory pressure (pressure-control) | 20 mbar   |
|                               | 30 mbar                 |
| Positive end-expiratory pressure (PEEP) | 6 mbar    |
|                               | 10 mbar 15 mbar         |
| Tidal volume (volume-control) | 900 mL (450x2)          |
| I:E ratio                     | 1:2                     |
| Breaths / minute              | 12                      |
| O2 concentration              | 50%                     |

Connection of the ventilator to the splitters, tubes, flow and pressure sensors, microbial filters and the test lungs was done as shown in figure 3. It would also be relevant to test the addition of one-way valves in the system, but this was not available for the tests. A photo of the test lungs connected to the flow and pressure sensors and the anesthetic machine is shown in figure 4. The lengths of all tubes were equal.

**Results**

Figure 5a shows how the distribution in ventilation between the two lungs was dependent on the differences in compliance between them. Expectedly, the tidal volumes were equal upon equal compliance, but the ventilation in Lung B was reduced to about 100 mL below target (450 mL) when its compliance was set to 20 mL/mbar. At the same time, Lung A received a higher tidal volume at more than 100 mL above target. At this point and also for lower compliances of Lung B, the pressure-limitation alarm of the machine would trigger. Lung B received even poorer ventilation of less than 50% of volume target for compliances of 14 and 7 mL/mbar. Turning off the pressure limitation (set to 80 mbar) did not help the ventilation of the stiffer lung considerably, but could lead to unwanted increases in volume and pressure into Lung A. The resistance into both lungs was kept at 5 mbar/L/s in this test.
Figure 3. Setup for the testing of two lungs sharing one ventilator with monitoring of tidal volumes and pressure into both lungs.

Figure 4. Test lungs, flow and pressure sensors and the anesthetic machine used in the study.
Figure 5. Distribution in ventilation between the two test lungs A and B, where A has a constant compliance at 28 mL/mbar while the compliance of lung B is changed (Cb in the figure). The tidal volume and pressure was measured both with pressure-limited ventilation (at 30 mbar) and without pressure limitation (set to 80 mbar). Tidal volume of each lung is shown in a) and the pressure into of each lung is shown in b). The measurements were done in volume-controlled ventilation mode.

Figure 6 shows how the ventilation also depended on the airway resistance. A comparison between figure 6a and b shows that the volume distribution between the lungs was unaffected by increasing the
resistance equally for both lungs, independent of the compliance in Lung B. Increasing only the resistance into Lung B gave a slight reduction in Lung B’s tidal volume, and correspondingly a slight increase in Lung B’s tidal volume was measured upon increasing only the resistance into Lung A. This change was small (28 mL at \( C_B = 20 \)) although the resistance was quadrupled, and there were no significant changes in pressure. This effect of differences in airway resistance on the tidal volume was also low in both volume and pressure controlled ventilation modes. A tenfold increase in the airway resistance into lung A caused a considerable increase in the tidal volume of lung B as shown in figure 7a, but only for \( C_B = 29 \) and 20 mL/mbar. At lower \( C_B \), the tidal volumes of both lungs were reduced compared to the non-constricted case (figure 6a), and a pressure drop into Lung A was measured (figure 7b).

Figure 6. The measured tidal volumes of both test lungs are shown for different compliances of lung B (\( C_B \)) at various airway resistances (\( R_A \) and \( R_B \)) to the lungs. The measurements were done in volume-controlled ventilation mode.
Figure 7. Distribution in ventilation between the two test lungs (a) and pressures into the lungs (b) for the case of a very high airway resistance into Lung A. The measurements were done in volume-controlled ventilation mode.

Figure 8a shows how the distribution in ventilation between the test lungs was dependent on ventilator mode, comparing volume-controlled ventilation to pressure-controlled ventilation at a maximum inspiratory pressure (Pmax) of 20 and 30 mbar. With pressure-controlled ventilation at Pmax=20, the less compliant lung received poorer ventilation compared to volume controlled mode. With pressure-controlled ventilation at Pmax=30 however, the less compliant lung received better ventilation compared to volume control mode, obtaining a tidal volume close to target at \( C_B = 20 \). At the lower levels of compliance, Lung B was still ventilated far below the target volume and the improvement compared to volume-control was marginal. It is also noteworthy that the pressures into the lungs were more equal in pressure control mode as shown in figure 8b.

As shown in figure 9, the distribution between the test lungs was also dependent on the extrinsic PEEP. A particularly noteworthy case was for \( C_B = 20 \), where a PEEP level of 10 mbar would seem to ventilate the two lungs more evenly than for a PEEP at 6, but when the PEEP was increased to 15, Lung A (the more compliant of the two) lost its tidal volume while lung B remained at the same level. In this case, the PEEP at 15 mbar had caused Lung A to remain highly inflated after expiration leaving little capacity for additional ventilation, while lung B was empty after expiration allowing more air to enter from the inspiratory pressure. This dependency on PEEP was approximately equal for volume and pressure controlled ventilation.
Figure 8. Tidal-volumes (a) and pressures (b) for the two test-lungs at volume-controlled ventilation (Vcon) compared to pressure-controlled ventilation (Pcon) at two levels of maximum inspiratory pressure (Pmax).
The combination of both increased Pmax at 30 mbar and increased PEEP at 10 mbar is shown in figure 10. In this mode, the ventilation of both lungs was quite equal and close to target for compliances of 29 and 20 mL/mbar in lung B. For lower compliances, the discrepancies in delivered tidal volumes became large. The pressures into the lungs were around 28 mbar and quite equal between the lungs for all levels of $C_B$. 

Figure 9. Tidal volumes and pressures for the two test-lungs using volume-controlled (a) and pressure-controlled (b) ventilation at different levels of extrinsic PEEP.
Discussions

The results clearly show how differences in compliance could cause large discrepancies in ventilation between the two test lungs, and that this difference was large (around 40%) when the stiffer lung had a 30% lower compliance than the other lung. Further reductions in compliance of the stiffer lung to 50% and below lead to even larger discrepancies, suggesting that connecting patients with such differences in compliance by this technique would cause very different delivery of tidal volumes from the same setting on the machine. In addition to insufficient ventilation of the stiffer lung, the problem of potentially causing volutrauma in the more compliant lung arises. These issues would not be any less problematic when connecting four patients to the same ventilator. Two randomly paired patients with ARDS could have relatively large differences in compliance, as the baseline variation between patients can be large (Amato et al. 1998, Gattinoni et al. 2006, Sundaresan et al. 2011), with a percentwise variation (std/mean) of about 23% to 40% from these studies. Perhaps even more important is the intraindividual changes in lung condition during the course of treatment and changes in compliance due to regular events such as changing the position of the patient, sudden obstruction due to secretion, coughing, or breathing in non-paralyzed patients.

An increased inspiratory pressure decreased the discrepancy in delivered tidal volumes, as shown in figure 8a with a Pmax at 30 mbar. The figure also shows that the distribution in ventilation between the lungs at CB=20 was improved at pressure-controlled ventilation compared to volume-controlled ventilation given that the Pmax was high enough. Too high pressures should however be avoided, and this setting of 30 mbar Pmax is close to the upper limit recommended for the plateau airway pressure (30 cmH20 = 29.4 mbar) in the treatment of ARDS from Covid-19 (Matthay et al. 2020).

Our results are largely in agreement with Branson et al. 2012, who also found a low effect of airway resistance differences compared to compliance differences in the volume distribution between test lungs. Branson et al. 2012 reported that the discrepancies in delivered tidal volumes was exacerbated for pressure-controlled ventilation (using a Pmax of 15 cm H2O), and this is also in agreement with our
results when Pmax was set to 20 mbar, but we found to the contrary a decreased discrepancy for higher Pmax.

As shown in figure 6, the changes in resistance of the airways had little effect on the ventilation volumes compared to the lung compliances. A quadrupling of the resistance into the more compliant test lung gave negligible changes to the ventilation of a test lung with 50% of the compliance. An idea for evening out the volume discrepancies has been circulating on the Internet, involving connecting a diaphragm valve into one or both of the inspiratory tubes for constriction of the flow to the more compliant lung in order to compensate for tidal volume differences. On our test lungs, a four-fold constriction had very little effect on the volume distribution between the lungs, and a tenfold constriction was necessary in order to even out the tidal volumes at Cb=20. With such a strong constriction, it could be difficult to tune the flow accurately within the cross-sectional area of the tube that is left. Comparing figures 6a and 7a, it is shown that at the two lower Cb levels, the constriction did not help in ventilating the stiffer lung, but also reduced the ventilation of the other lung. Another issue with constriction and increase of airway resistances is the changes to the inspiratory time constant, which in this example would be 1.4s for inspiration of Lung A and 0.1s for Lung B – a 14-fold difference.

The extrinsic PEEP was set to 6 mbar as default for all tests until the PEEP was increased to 10 and 15 mbar while the compliance-dependent ventilation distribution between the lungs was studied. Going from 6 to 10 mbar PEEP, the tidal volumes of the two lungs became more equal, especially notable when Cb=20. Our next finding was that further increases in PEEP could greatly influence the tidal volumes of the two test lungs and in unintended ways. The PEEP setting is used in treatment to sustain a positive pressure after the end of expiration to prevent alveolar collapse, but this effect could be quite different when several lungs are connected to the same inspiratory and expiratory valves. As shown in figure 9, the distribution in tidal volumes was strongly dependent on the PEEP, and at Cb=20 Lung B obtained about three times the tidal volume of Lung A although Lung A was more compliant. In this case, Lung A was largely inflated after expiration while Lung B was empty. This indicates an additional potential problem in ventilating lungs with different compliances when the PEEP is high. The “two-balloon effect” (Merritt and Weinhaus 1978) could possibly have contributed to this volume discrepancy, and the inclusion of one-way valves could possibly help. This is the first study to our knowledge to include testing of split ventilation using moderate to high PEEP levels, which is recommended for consideration in the treatment of ARDS from Covid-19 (Matthay et al. 2020).

In summary, balanced ventilation of two lungs could expectedly be obtained for two equal test lungs, but the distribution of ventilation between the lungs was strongly dependent on compliance differences and in interaction with higher extrinsic PEEP levels. When the compliance of one lung was 50% or less than the other lung, we did not obtain balanced ventilation for any of the ventilator settings. When the compliance of one lung was around 30% less than the other lung, more equal tidal volumes were measured when using pressure-controlled ventilation with a Pmax of 30 mbar and a PEEP at 6 or 10 mbar.

It is important to stress that experimenting on test lungs have obvious limitations and is far from the real situation with ventilation of real pathological lungs over many days with additional concerns such as contamination, coughs and voluntary breathing triggering the ventilator, and the extrapolation of these experiments to the treatment of real lungs is limited. The test lungs used in the study will have different characteristics from lungs in ARDS patients, including the levels of compliance and the pressure-volume
characteristics. The used test lungs had adjustable compliance from 10 to 30 mL/mbar (in reality 7-29 mL/mbar), which is far less than expected for healthy lungs. Anyhow, our main goal was to investigate the distribution of ventilation for lungs with relative differences in compliance. At the same time, this should be taken into consideration when interpreting our results on patients with other compliance levels. The observed effects of PEEP in test lung with different compliance will likely be of clinical relevance in patients with ARDS as personalized, where elevated PEEP often is indicated. In patients with severe lung failure due to ARDS the optimal combination between pressure, flow and PEEP is sought. Individualized therapy will not be possible when one respirator is shared between two or more patients.

It would have been natural to also test the inclusion of one-way valves in the system as this has already been suggested as an improvement. This was unfortunately not available for the experiments and we cannot say for sure how this would have affected the ventilation distribution between the test lungs.

Sharing one respirator on two or more patients will complicate monitoring of all included patients and the competence and clinical skills of the critical care nurse or physician will be crucial. The respirator mode is individualized based on measurements of flow, pressure, and end-tidal CO2. In a patient safety perspective, a simple pressure controlled ventilator mode with moderate PEEP in patients with comparable respiration physiology is indicated.

The solution introduced by Neyman and Babcock Irvin is very simple, but there are hazards and problems as mentioned above. We are therefore investigating possible improvements for safety and performance, including:

- One-way valves on the inspiratory and expiratory tubes.
- Pressure-reduction valves (or constrictions) in series with the inspiratory tubes. This could possibly benefit form automatic control by a programmable logic controller (PLC).
- Rapid on-off valves combined with flow and pressure sensing on the patient side continually monitored by a PLC.

**Conclusion**

We found large discrepancies in delivered tidal volumes for paired test lungs with compliance differences, little influence from differences in airway resistances, and that higher PEEP settings could strongly influence the tidal volume balance between the test lungs. The most balanced, although far from ideal, delivery of tidal volumes for test lungs with different compliance was measured using pressure-controlled ventilation with a Pmax of 30 mbar and a PEEP at 6 or 10 mbar. From this study and from a technical point of view, we were not able to identify reliable settings, adjustments or any simple measures to overcome the hazards of the technique.

**Acknowledgements**

The authors would like to thank Professor Richard Branson from the University of Cincinnati and Professor Erwan L'Her from Université de Bretagne Occidentale for sharing of knowledge, experiences and helpful discussions.
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Dataset
The measured data are available upon request.