Simulated ventilation of two patients with a single ventilator in a pandemic setting

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**INTRODUCTION**

The coronavirus disease 2019 (COVID-19) pandemic broke out in 2020-3 due to fast developing of great numbers of adult respiratory distress syndrome patients.4,5 However, there was a dramatic shortage of experienced staff, medical equipment and, in particular, ventilators in hospitals.6,7 Even in autumn 2021, almost 2 years after the outbreak of the pandemic, there is a real crisis in intensive care unit resources due to COVID-19 in Romania and Bulgaria, leading to emergency transfers of patients to other European Union countries. Such situations were unimaginable in western industrialized countries before the COVID-19 pandemic. In desperate situations in the last 2 years, people have even tried to share one ventilator for two patients. However, due to differences in resistance and lung compliance, this can lead to hypoventilation in one patient and hyperinflation in the other, which can cause lung damage and have a negative impact on morbidity and mortality.

A simple solution to distribute the tidal volume of a ventilator between two patients may be a three-dimensional (3D) printed Y-adapter, which has been reported during the 9/11 terrorist attacks and Hurricane Katrina in New Orleans, USA.8 Recent reports from the United States indicate that similar devices were also used in the COVID-19 pandemic.9 Historical studies have demonstrated this strategy in a laboratory setting.8 However, as the tidal volume cannot be adequately distributed to each patient, mainly due to differences in resistance and lung compliance, this can result in hypoventilation in one patient and hyperinflation in the other. This may result in hypercarbia or even hypoxemia in a given patient with the “worse” lung, while the better lung may be hyperinflated and severely damaged.10,11 To avoid this misalignment between patients, we developed a 3D printed stenosis adapter that can be inserted into a patient’s breathing tube. This theoretically allows the tidal volume to be variably distributed between patients.

We evaluated gas distribution in a ventilation bench model using artificial lungs with equal lung compliance during volume-controlled and pressure-controlled ventilation by inserting stenosis adapters of 2–9 mm. Subsequently, we modified the model using a special one-way valve and evaluated in pressure-controlled ventilation mode the influence of these stenosis adapters on gas distribution between lungs with different lung compliance settings representing ventilation of standard intensive care patients vs. acute respiratory distress syndrome patients, e.g., due to COVID-19. Our formal hypothesis was that there would be no difference between groups.

**MATERIALS AND METHODS**

**Experimental setup**

We have developed a Y-adapter that fits a modern ventilator according to ISO 5356-112 (Figure 1A). This adapter can be used in both the inspiratory and expiratory branches of the breathing tube. Accordingly, we have developed flow restrictors with a diameter of 2–9 mm that can be inserted into ventilation tubes (Figure 1B).
Both pieces were made of carbon fiber (Multec Carbon, Multec, Illmensee, Germany) and printed on a standard 3D printer which have been widely available in the past few years (Multec Multirap M800, Multec, Illmensee, Germany). The average printing time was 4 hours; the adapter could be disinfected and sterilized.

For lung and airway simulation, we used a dual test lung with lung compliance and airway resistance separately adjustable in each test lung (dual Adult TTL - Model 5600i, Michigan Instruments, Grand Rapids, MI, USA). In this way, each side of the lung was set to represent the airway characteristics of a single patient; consequently, the dual lung represented the airway characteristics of two patients. To determine minute ventilation, we placed a respirometer (Ferraris, Hertford, UK) in the tubes connecting the ventilator to each of the separate lungs, simulating one patient.

We adjusted the Y-adapter with a modern ventilator (Hamilton C6, Bonaduz, Switzerland) in different positions to ventilate both test lungs independently (Figure 2).

In the first setup, we used Y- adaptors in both the inspiratory and expiratory circuits, which we connected to standard double-lumen breathing tubes to test the lungs. The flow limiter was set on the side of lung B directly behind the inspiratory adapter and the flow sensor was set on the circuit to test lung A. This setting allowed expiratory gas to flow back to the ventilator from both test lungs (Figure 2A). In the second setup, we used only one Y-adapter in the inspiratory circuit and connected only lung B via a standard double lumen connecting tube, allowing expiratory gas to flow back to the ventilator from lung B only. Test lung A was connected to the ventilator via a single-lumen connecting tube; at the distal end in front of test lung A, we attached a connector of an AMBU Mark V bag-valve device (Ambu Glostrup, Copenhagen, Denmark); thus, the expired gas was vented directly into the ambient air near test lung A and did not flow back to the ventilator via a double-lumen tube as in setup 1. The flow restrictor was also integrated into circuit B, as in setup one. The flow sensor was placed on the double lumen side of circuit B (Figure 2B). In a third setup, lung A was connected to a standard double lumen connecting tube, allowing expired gas from lung A to flow back to the ventilator. The one-way tube was connected to lung B; we adjusted both the flow restrictor distal to the Y-adapter and the expiratory valve of an AMBU Mark V bag-valve device (Ambu Glostrup, Copenhagen, Denmark) in circuit B. As a result, ventilation to lung B was both limited and the expiratory gas flow from lung B was directed into the ambient air and not back to the ventilator. The flow sensor was set to the standard double lumen side of circuit A (Figure 2C).

**Experimental procedure**

A total of six experiments were performed in the above setups; each experiment was performed for 1 minute and repeated six times. The first two experiments were performed in setup one. In the first experiment (Figure 2A), both lungs were ventilated in volume-controlled mode with a compliance of 30 mL/mbar, simulating moderate acute respiratory distress syndrome in both lungs (respiratory rate 12/min, tidal volume 1200 mL, Pmax 2 kPa, positive end-expiratory pressure (PEEP) 5 mbar, inspiratory oxygen fraction 0.21, inspiratory to expiratory time ratio 1:2). The first measurement was performed without flow limiter. Subsequently, flow limiters with decreasing diameters (9–2 mm) were integrated into the inspiratory tube connected to lung B. The second experiment was performed in pressure-controlled mode in the same first setup (respiratory rate 12/min, Pmax 20 mbar, PEEP 5 mbar, inspiratory oxygen fraction 0.21, inspiratory to expiratory time ratio 1:2). In all pressure-controlled experiments, the peak pressure was adjusted to achieve a tidal volume of 600 mL in

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**Figure 1:** Y-adapter and stenosis adapter. Note: (A) The draft of a 3D printable Y-adapter can be used to divert gas flow to two patients according to ISO 5356-1. (B) Draft of a 3D printable “Flow limiter” created in Autodesk Fusion 360 according to ISO 5356-1: variable inside diameter from 2–9 mm.

**Figure 2:** Illustration of a Hamilton C6 ventilator connected to two test lungs. Note: (A) Ventilation of two test lungs with a Y-adapter in the in- and expiratory ventilator thigh over two double ventilation hoses. The flow limiter is placed in circuit B, the flow sensor in circuit B. (B) Ventilation of two lungs with only one Y-adapter in the inspiration thigh. The flow limiter is placed in circuit B. Expiration in circuit A over a one-way expiration valve with an optional PEEP valve. The flow sensor is placed in circuit B (double hose). (C) Ventilation of two lungs with Y-adapter in the inspiration thigh. Expiration in circuit A over a one-way expiration valve with an optional PEEP valve. The flow sensor is placed in circuit A. Circuit B double hose. PEEP: Positive end-expiratory pressure.
unobstructed lung A. As the measurements were performed with different compliances, this volume was adjusted for each experiment. The third experiment was performed in the second setup (Figure 2B). The peak inspiratory pressure was chosen to give a tidal volume in lung A of 600 mL. The compliance of test lung A was 70 mL/mbar to simulate a healthy lung. The fourth experiment was pressure-controlled ventilation, similar to experiments 2 and 3 in the third setup (Figure 2C) and compared the ventilatory parameters of test lung A with a compliance of 50 mL/mbar in both lungs. The fifth experiment was again performed in setup three (Figure 2C) and compared the ventilatory parameters of test lung A with a compliance of 30 mL/mbar with the ventilatory parameters of test lung B with 70 mL/mbar. The sixth experiment was also performed in setup three (Figure 2C) and compared the ventilatory parameters of test lung A with a compliance of 30 mL/mbar with the ventilatory parameters of test lung B with 70 mL/mbar. Ventilation pressure was always set to achieve tidal volumes of 600 mL on the unobstructed side.

**Statistical analysis**

Statistical evaluation was performed with SigmaPlot 14 (Systat, San Jose, CA, USA) using Student’s t-test after Shapiro-Wilk analysis for normality and equal variance test (Brown-Forsythe). If a normality test failed, the Mann-Whitney rank sum test was used. Data are presented as mean ± standard deviation (SD). P values < 0.05 were considered significant.

**Results**

In experiments 1 and 2, we measured comparable minute volumes in both lungs using either volume- or flow-controlled ventilation, regardless of the use of flow limiters (Tables 1 and 2). The volume-controlled ventilation mode resulted in a severe continuous disconnection alarm, although ventilation was adequate (Table 1). In experiment 3, flow limitation distributed the tidal volume to lung A. However, lung A was moderately hyperventilated when smaller diameter flow limiters were used (Table 3). In experiment 4, flow limiters effectively reduced the volume on the obstructed side while adequately ventilating lung A (Table 4). In experiments 5 and 6, simultaneous ventilation of two lungs with different compliance was possible by inserting flow limiters of < 6 mm flow diameter in the tube to lung B with better compliance (Tables 5 and 6).

**Discussion**

In this study we show the evaluation process of using flow limiters to direct tidal volume to one lung. Simulated ventilation of two patients with a single ventilator was technically possible using both volume- and pressure-controlled ventila-

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### Table 1: Volume-controlled mode with the same compliance in both lungs of 30 mL/mbar (Experiment 1)

| Y-adapter inside diameter | Test lung A M.V. (L/min) | Test lung B M.V. (L/min) | F.S. C6 (A) M.V. (L/min) | Hamilton C6 peak pressure (mbar) | P (test lung A vs. B) |
|--------------------------|--------------------------|--------------------------|--------------------------|----------------------------------|----------------------|
| A: Φ 19 mm, B: Φ 19 mm   | 6.4 ± 0.4                | 6.8 ± 0.3                | 6.2 ± 0.1                | 28 ± 0                            | 0.25                 |
| A: Φ 19 mm, B: Φ 9 mm    | 6.3 ± 0.4                | 6.9 ± 0.3                | 6.3 ± 0.1                | 28 ± 0                            | 0.03                 |
| A: Φ 19 mm, B: Φ 8 mm    | 6.4 ± 0.3                | 6.7 ± 0.1                | 6.1 ± 0.1                | 28 ± 0                            | 0.12                 |
| A: Φ 19 mm, B: Φ 7 mm    | 6.6 ± 0.3                | 6.7 ± 0.2                | 5.8 ± 0.1                | 28 ± 0                            | 0.09                 |
| A: Φ 19 mm, B: Φ 6 mm    | 6.6 ± 0.4                | 6.7 ± 0.2                | 6.1 ± 0.1                | 28 ± 0                            | 0.12                 |
| A: Φ 19 mm, B: Φ 5 mm    | 6.7 ± 0.2                | 6.6 ± 0.1                | 6.0 ± 0.2                | 28 ± 0                            | 0.35                 |
| A: Φ 19 mm, B: Φ 4 mm    | 6.5 ± 0.2                | 6.5 ± 0.1                | 5.8 ± 0.1                | 27 ± 0                            | 0.35                 |
| A: Φ 19 mm, B: Φ 3 mm    | 6.5 ± 0.2                | 6.4 ± 0.1                | 5.7 ± 0.2                | 27 ± 0                            | 0.92                 |
| A: Φ 19 mm, B: Φ 2 mm    | 6.6 ± 0.2                | 6.5 ± 0.1                | 5.7 ± 0.1                | 27 ± 0                            | 0.22                 |

Note: Lung A: Inside diameter of the Y-adapter according to ISO 5356-1; lung B: With and without (19 mm) limitation of the inside diameter of the flow limiter. Flow limitation on circuit B flow sensor on circuit A, double hose circuit for lungs A and B. If the flow sensor is connected prior to test lung B and not prior to the Y-adapter stop of ventilation; F.S. = flow sensor on circuit A. Continuous alarm of the ventilator. Disconnection on patient-side alarm. M.V.: minute ventilation.

### Table 2: Pressure-controlled ventilation with the same compliance of 30 mL/mbar in both lungs (Experiment 2)

| Y-adapter inside diameter | Test lung A M.V. (L/min) | Test lung B M.V. (L/min) | F.S. C6 (A) M.V. (L/min) | Hamilton C6 peak pressure (mbar) | P (test lung A vs. B) |
|--------------------------|--------------------------|--------------------------|--------------------------|----------------------------------|----------------------|
| A: Φ 19 mm, B: Φ 19 mm   | 7.6 ± 0.2                | 7.8 ± 0.3                | 7.1 ± 0.1                | 28 ± 0                            | 0.34                 |
| A: Φ 19 mm, B: Φ 9 mm    | 7.4 ± 0.2                | 7.9 ± 0.2                | 6.8 ± 0.1                | 28 ± 0                            | 0.03                 |
| A: Φ 19 mm, B: Φ 8 mm    | 7.5 ± 0.3                | 7.9 ± 0.2                | 7.3 ± 0.1                | 28 ± 0                            | 0.08                 |
| A: Φ 19 mm, B: Φ 7 mm    | 7.5 ± 0.1                | 8.0 ± 0.1                | 7.2 ± 0.1                | 28 ± 0                            | 0.03                 |
| A: Φ 19 mm, B: Φ 6 mm    | 7.5 ± 0.1                | 7.9 ± 0.1                | 7.1 ± 0.1                | 28 ± 0                            | 0.03                 |
| A: Φ 19 mm, B: Φ 5 mm    | 7.4 ± 0.1                | 7.5 ± 0.1                | 7.1 ± 0.1                | 28 ± 0                            | 0.04                 |
| A: Φ 19 mm, B: Φ 4 mm    | 7.4 ± 0.1                | 7.4 ± 0.1                | 7.1 ± 0.1                | 26 ± 0                            | 0.35                 |
| A: Φ 19 mm, B: Φ 3 mm    | 7.4 ± 0.1                | 7.2 ± 0.1                | 7.0 ± 0.1                | 26 ± 0                            | 0.03                 |
| A: Φ 19 mm, B: Φ 2 mm    | 7.4 ± 0.1                | 7.1 ± 0.1                | 7.1 ± 0.1                | 26 ± 0                            | 0.03                 |

Note: Lung A: Inside diameter of the Y-adapter according to ISO 5356-1; lung B: With and without (19 mm) limitation of the inside diameter of the flow limiter. Flow limitation on circuit B flow sensor on circuit A, double hose circuit for lungs A and B. If the flow sensor is attached to lung B, F.S. = flow sensor on circuit A. No ventilator alarm. M.V.: minute ventilation.
### Table 3: Pressure-controlled ventilation with the same compliance in both lungs of 70 mL/mbar (Experiment 3)

| Y-adapter inside diameter | Test lung A M.V. (L/min) | Test lung B M.V. (L/min) | Hamilton C6 M.V. (L/min) | Hamilton C6 peak pressure (mbar) \(\text{P (test lung A vs. B)}\) |
|---------------------------|--------------------------|--------------------------|--------------------------|-----------------------------------------------------------------|
| A: Φ 19 mm, B: Φ 19 mm   | 8.1 ± 0.4                | 7.8 ± 0.4                | 6.8 ± 0.2                | 14 ± 0 0.3                                                        |
| A: Φ 19 mm, B: Φ 9 mm    | 8.9 ± 0.2                | 7.9 ± 0.5                | 6.9 ± 0.11               | 14 ± 0 0.04                                                      |
| A: Φ 19 mm, B: Φ 8 mm    | 9.3 ± 0.3                | 8.0 ± 0.4                | 6.6 ± 0.2                | 14 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 7 mm    | 9.4 ± 0.2                | 7.8 ± 0.1                | 6.2 ± 0.2                | 14 ± 0 0.002                                                    |
| A: Φ 19 mm, B: Φ 6 mm    | 9.6 ± 0.1                | 7.9 ± 0.3                | 6.7 ± 0.0                | 14 ± 0 0.002                                                    |
| A: Φ 19 mm, B: Φ 5 mm    | 10.5 ± 0.0               | 7.9 ± 0.1                | 6.9 ± 0.1                | 14 ± 0 0.002                                                    |
| A: Φ 19 mm, B: Φ 4 mm    | 10.2 ± 0.1               | 6.0 ± 0.1                | 5.4 ± 0.1                | 14 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 3 mm    | 9.4 ± 0.3                | 3.5 ± 0.1                | 3.0 ± 0.2                | 13 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 2 mm    | Failed                   |                          |                          |                                                                 |

Note: Lung A: Inside diameter of the Y-adapter according to ISO 5356-1; lung B: With and without (19 mm) limitation of the inside diameter by the flow limiter. Flow limitation on circuit B and flow sensor on circuit A. Single hose in circuit A and a double hose in circuit B. *Adjustment of the upper ventilation pressure to 14 mbar due to a change in lung compliance test lung A. M.V.: Minute ventilation.

### Table 4: Pressure-controlled ventilation with the same compliance in both lungs of 70 mL/mbar (Experiment 4)

| Y-adapter inside diameter | Test lung A M.V. (L/min) | Test lung B M.V. (L/min) | Hamilton C6 M.V. (L/min) | Hamilton C6 peak pressure (mbar) \(\text{P (test lung A vs. B)}\) |
|---------------------------|--------------------------|--------------------------|--------------------------|-----------------------------------------------------------------|
| A: Φ 19 mm, B: Φ 19 mm   | 8.0 ± 0.4                | 7.8 ± 0.4                | 7.2 ± 0.1                | 14 ± 0 0.3                                                        |
| A: Φ 19 mm, B: Φ 9 mm    | 6.7 ± 0.1                | 6.6 ± 0.1                | 6.7 ± 0.1                | 14 ± 0 0.25                                                      |
| A: Φ 19 mm, B: Φ 8 mm    | 7.5 ± 0.3                | 6.5 ± 0.2                | 6.7 ± 0.0                | 14 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 7 mm    | 7.9 ± 0.0                | 7.0 ± 0.0                | 6.7 ± 0.0                | 14 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 6 mm    | 7.5 ± 0.1                | 6.5 ± 0.1                | 6.7 ± 0.0                | 14 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 5 mm    | 7.8 ± 0.1                | 6.5 ± 0.1                | 6.7 ± 0.0                | 14 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 4 mm    | 7.5 ± 0.0                | 5.0 ± 0.0                | 6.7 ± 0.0                | 14 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 3 mm    | 7.7 ± 0.1                | 3.0 ± 0.0                | 6.7 ± 0.0                | 14 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 2 mm    | 7.4 ± 0.2                | 0.8 ± 0.0                | 6.7 ± 0.0                | 14 ± 0 0.001                                                    |

Note: Lung A: Inside diameter of the Y-adapter according to ISO 5356-1; lung B: With and without (19 mm) limitation of the inside diameter by the flow limiter. Flow limitation on circuit B and flow sensor on circuit A. Single hose in circuit A and a double hose in circuit B. *Adjustment of the upper ventilation pressure to 14 mbar due to a change in lung compliance test lung A. M.V.: Minute ventilation.

### Table 5: Pressure-controlled ventilation with compliance of 50 mL/mbar in Lung A and 70 mL/mbar in Lung B (Experiment 5)

| Y-adapter inside diameter | Test lung A M.V. (L/min) | Test lung B M.V. (L/min) | Hamilton C6 M.V. (L/min) | Hamilton C6 peak pressure (mbar) \(\text{P (test lung A vs. B)}\) |
|---------------------------|--------------------------|--------------------------|--------------------------|-----------------------------------------------------------------|
| A: Φ 19 mm, B: Φ 19 mm   | 7.4 ± 0.1                | 9.6 ± 0.2                | 7.2 ± 0.1                | 18 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 6 mm    | 7.6 ± 0.2                | 9.4 ± 0.4                | 6.9 ± 0.0                | 18 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 5 mm    | 7.6 ± 0.0                | 8.5 ± 0.1                | 6.9 ± 0.0                | 18 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 4 mm    | 7.4 ± 0.0                | 6.6 ± 0.0                | 6.9 ± 0.0                | 18 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 3 mm    | 7.2 ± 0.0                | 4.1 ± 0.0                | 6.9 ± 0.0                | 18 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 2 mm    | 7.2 ± 0.0                | 1.2 ± 0.1                | 6.9 ± 0.0                | 18 ± 0 0.001                                                    |

Note: Flow limitation on circuit B and flow sensor on circuit A. Single hose in circuit B and a double hose in circuit A. Lung A: Inside diameter of the Y-adapter according to ISO 5356-1; lung B: With and without (19 mm) limitation of the inside diameter by the flow limiter. Flow limitation on circuit B and flow sensor on circuit A. Single hose in circuit B and a double hose in circuit A. *Adjustment of the upper ventilation pressure to 26 mbar due to a change in lung compliance test lung A. M.V.: Minute ventilation.

### Table 6: Pressure-controlled ventilation with compliance of 30 mL/mbar in Lung A and 70 mL/mbar in Lung B (Experiment 6)

| Y-adapter inside diameter | Test lung A M.V. (L/min) | Test lung B M.V. (L/min) | Hamilton C6 M.V. (L/min) | Hamilton C6 peak pressure (mbar) \(\text{P (test lung A vs. B)}\) |
|---------------------------|--------------------------|--------------------------|--------------------------|-----------------------------------------------------------------|
| A: Φ 19 mm, B: Φ 19 mm   | 7.0 ± 0.1                | 14.5 ± 0.2               | 7.2 ± 0.1                | 26 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 6 mm    | 7.5 ± 0.1                | 14.5 ± 0.4               | 6.7 ± 0.0                | 26 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 5 mm    | 7.4 ± 0.0                | 12.0 ± 0.1               | 6.7 ± 0.0                | 26 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 4 mm    | 7.3 ± 0.0                | 9.0 ± 0.0                | 6.7 ± 0.0                | 26 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 3 mm    | 7.2 ± 0.2                | 5.7 ± 0.0                | 6.7 ± 0.0                | 26 ± 0 0.001                                                    |
| A: Φ 19 mm, B: Φ 2 mm    | 7.2 ± 0.2                | 2.0 ± 0.1                | 6.7 ± 0.0                | 26 ± 0 0.001                                                    |

Note: Lung A: Inside diameter of the Y-adapter according to ISO 5356-1; lung B: With and without (19 mm) limitation of the inside diameter by the flow limiter. Flow limitation on circuit B and flow sensor on circuit A. Single hose in circuit A and a double hose in circuit B. *Adjustment of the upper ventilation pressure to 26 mbar due to a change in lung compliance test lung A. M.V.: Minute ventilation.
Gas flow limitation by flow restrictors was not possible in the first setting when standard double tube circuits were used on both lungs. We speculate that by using two Y-adapters in the inspiratory and expiratory circuits, we increased the pressure first in the unobstructed inspiratory circuit and then in the expiratory circuit on that side. This may have been due to the second Y-adapter on the expiratory side of the ventilator causing a faster increase in pressure on the expiratory side of the obstructed circuit than on the inspiratory side. As a result, the obstructed lung may have been ventilated retrogradely via the expiratory tube on the obstructed side (Additional Videos 1 and 2). As a result, we were unable to direct gas to one lung using flow restrictors in setup one.

We changed the setup by introducing a one-way valve with an additional PEEP adapter to lung A. As a result, only gas from lung B flowed back to the ventilator, avoiding this error in setup two. When the ventilator flow sensor was connected to the obstructed side, ventilation with ventilator effort was still possible up to a diameter of 3 mm and failed only at a diameter of 2 mm. We suggest that modern, powerful ventilators can ventilate through a 3 mm stenosis, comparable to small neonatal ventilation tubes, and thus overcome our at-
tempts at unilateral volume limitation. However, this resulted in hyperventilation of the unobstructed side, which could be detrimental in a real clinical setting. We therefore dropped this setting as well. We then further modified to setup three, which worked reliably with different lung compliance (experiments 4–6). We have deliberately included the failed experiments 1–3 in this manuscript to demonstrate the complexity of the whole development process. This study shows that using a particular ventilator in two patients without first validating it's specific working setup in test lungs can lead to immediate failure.

To deliver significant minute ventilation to a patient, flow limiters of < 6 mm generally had to be used. This contrasts with previous suggestions that much larger diameters (11–16 mm) should be used for this purpose; the use of such large diameters in our setting resulted in severe hyperinflation and lung overinflation in lungs with better compliance. Other studies have used adjustable flow limiters or a ventilator-adjusted Hoffmann clamp to increase inspiratory resistance, but the exact diameters in these settings are not known and cannot be standardized. The use of pressure control valves to distribute gas between two patients as a completely different solution has also been reported. At present, it is not known which system is the most promising; our solution is standardized and fully reproducible in terms of the diameters used. To further standardize the model, we deliberately chose to combine the flow sensor always with the standard double lumen tube as the original manufacturer’s product, the other side was always connected to the one-way valve.

Interestingly, the ventilator is indeed completely blind to the real situation on the side without the flow sensor; for example, it calculated a minute volume of 7 L in experiment 6, whereas we measured minute volumes > 20 L/min in the test lungs. Therefore, it may not even detect detrimental deviations. Thus, overriding the safety features of a modern ventilator would create a setting that requires very skilled monitoring by a highly experienced healthcare worker and would still be dangerous; the minimum personal monitoring parameters might be TV for each patient, maximum airway pressure and PEEP levels. These dangers and our concerns are in accordance with the recommendations of Society of critical Care Medicine did not recommend simultaneous ventilation at the beginning of the pandemic and the U.S. Food and Drug Administration sets narrow limits such as special ventilators, or special ventilation protocols.

In addition, patients cannot be allowed to spontaneously ventilate when flow limiters are in use, as the patient on the limited side would be in a situation of acute airway obstruction, which would compromise any weaning attempts. Furthermore, proper alarm management is not possible if the ventilator's safety features have to be overridden before this strategy can work. In addition, patients would have to be placed next to each other, facilitating aerosol exchange and cross-infection. Refusing a ventilator to one patient clearly has an impact on that patient, but using the system described on two patients could result in injury or death to both. This remains an ethical dilemma that can only be answered in a situation of acute crisis. Accordingly, although it works perfectly in this laboratory setting, such a setting is only conceivable in a desperate situation for a limited time after emergency intubation in deeply sedated patients to bridge until a second ventilator becomes available. Furthermore, our data, if applicable, only support the use of the specific ventilator used in this study; the use of another ventilator may require a substantially different approach. Failure to test this specific design prior to trial may result in immediate failure, as demonstrated by our failed setups one and two.

In addition, a home-printed adapter is not compliant with European Union or other medical device guidelines. We therefore tested in this technical model to test our hypothesis without any risk to patients.

In conclusion, it is possible to override the safety features of a modern intensive care ventilator and thus direct tidal volumes in different lung conditions to one lung using 3D-printed flow limiters. While this ventilation setting was technically feasible in a bench model, it would be unstable, if not dangerous, in a clinical situation.

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Author contributions
All authors contributed to the study conception. The first protocol was designed by PS, VW and HH. Material preparation, data collection and analysis were performed by PS, BK, ME and HH. The first draft of the manuscript was written by PS and HH, and all authors commented on previous versions of the manuscript. All authors read and
