A better way of connecting multiple patients to a single ventilator

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This differential multiventilation setup yields increased safety, monitoring and control for each connected patient.

In an ideal world, no one treating patients with Acute Respiratory Distress Syndrome (ARDS) would have to connect multiple patients to a single ventilator. However, the current SARS-CoV-2 pandemic leaves us in a far from ideal world, and healthcare professionals in hard-hit regions will have to strike a balance between the resources available and the resources their patients need. In the most extreme case, they might thus have to consider the unseemly solution of connecting multiple patients to a single ventilator (Branson et al., 2012; Branson & Rubinson, 2008; Farkas, 2020; Iserson, 2012; Neyman & Irvin, 2006; Paladino et al., 2008a, 2008b; Sommer et al., 1994).

Simply adding splitters to the breathing circuits (Neyman & Irvin, 2006) is the most rudimentary way of achieving this, but in this way, all systems to monitor and control the parameters for each different patient in the circuit are lost (Branson & Rubinson, 2008; Paladino et al., 2008a). Given that patients with COVID-19 need very different and precisely fine-tuned ventilator settings, treating them in this way becomes very hard.

As a Belgian team consisting of anesthesiologists, intensivists and (ventilator) engineers we have, in the past few days, tested circuits with added components to increase the

safety, monitoring and control for each patient. Our motto remained KISS, or Keep it Straightforward and Simple:

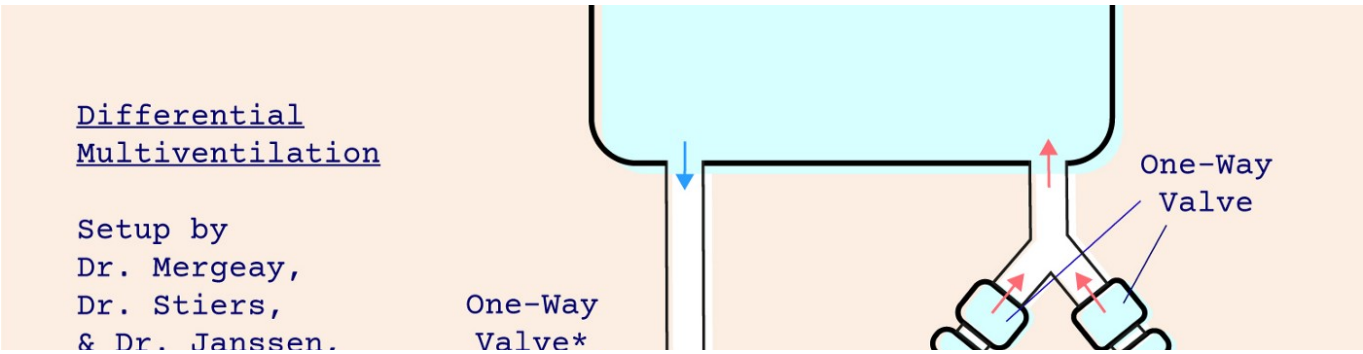
- **All the proposed components are readily available in hospitals, can be bought in medical supply or plumbing stores, and some can even be 3D printed as a back up plan,**
- **the setup contains no added electronics or software and should be easy to understand and implement for experienced caretakers,**
- **still, the setup allows the caretaker to monitor and finetune the pressure for each patient individually.**
- **The setup has also been tested for over 48h on test lungs, and it has been replicated by an independent testing facility.**

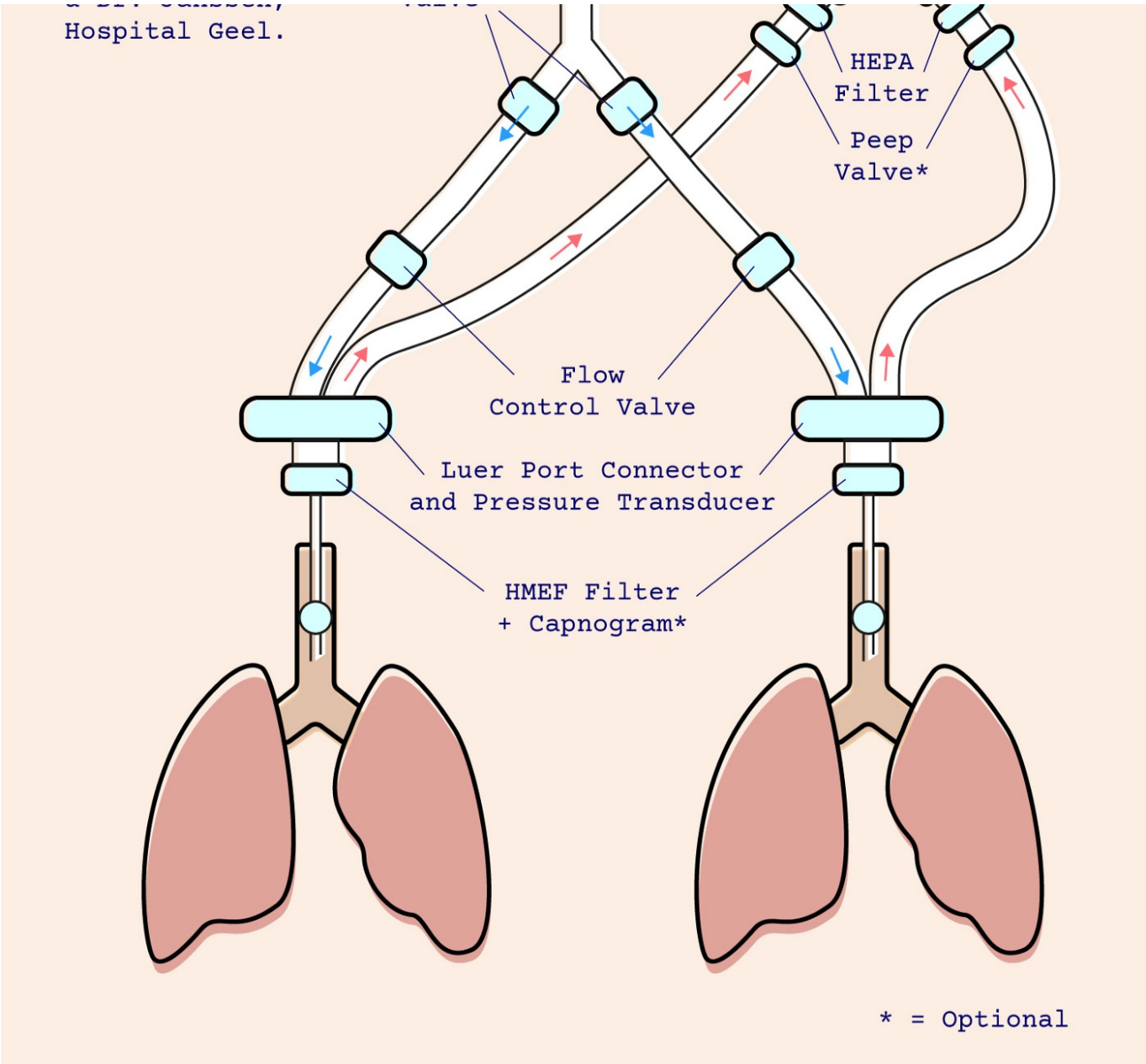
We would like to stress the fact that this has **not** been used in a clinical setting, and that we do **not** consider the testing complete. It is by no means anything else than a **last resort solution**. But given the short time and extreme circumstances, we would like to share this setup here with everyone interested to replicate and test it. If you are an expert on this topic, please let us know what you think. We're particularly interested in the results of replicating this system under different circumstances.

Overview of the proposed Differential Multiventilation setup

Originally designed by Dr. Margeay, M.D., Dr. Michiel Stiers, M.D., and Dr. Janssen, M.D., hospital Geel, Belgium.

Schematic representation





Movie of the setup with test lungs

A movie by Dr. Mergeay, hospital Geel, explaining the differential multiventilation setup.

How to obtain the components and set up the circuit

(Mentioned product links are not meant as commercial endorsements, merely as the quickest way to show examples.)

Full list of components

- 4 splitters for 2 patients, 6 splitters for 4 patients.
- 1 one-way valve per patient. For certain types of ventilators, 2 one-way valves per patient, one for expiration and one for inspiration, are advisable. See *'Effects of adding one-way valves in the inspiration circuits'*.
- 1 flow control valve per patient.
- 1 pressure transducer per patient.
- 1 HMEF filter per patient.
- Optional: 1 PEEP valve per patient.
- Optional: 1 capnogram per patient.
- Connectors with Luer ports, if additional ports are needed.
- 1 HEPA filter per patient.

Splitters

Add splitters on the inhalation and exhalation circuits; you will need four splitters for two patients, and six splitters to make a branching structure for four patients. Use zip ties to ensure the connection.

These splitters are usually available in hospitals, can be bought from medical supply stores or can be 3D printed.

One-way valves

Add a one-way valve (or 'check valve') on each *expiration* circuit. The valves on the expiration circuit are crucial to prevent backflow between the patients.

In some cases or for some ventilator types it might be advisable to add these one-way valves on the inspiration circuits as well. See section 'effects of adding one-way valves in the inspiration circuits' below.

These valves could be available in hospitals or can be bought from medical supply stores. We're currently looking into the possibility of 3D printing.

Flow control valve

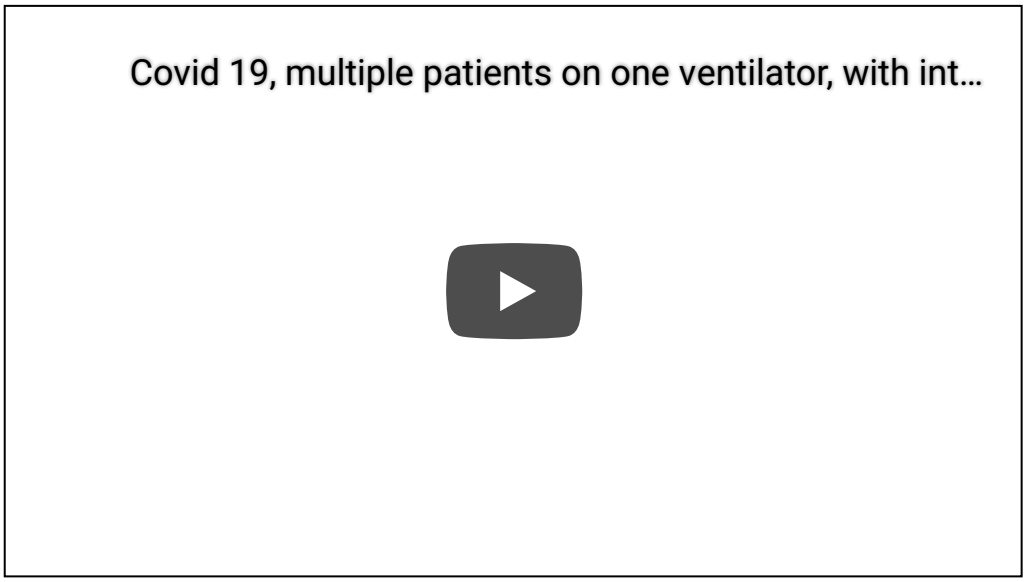
Add a flow control valve on each inspiration circuit. This valve can be used to change the pressure for each connected patient.

It can be a commonly available balancing valve, of the kind used in central heating and tap water systems. A plumber will have them, and will be able to prepare it for the ventilator tubing size. Especially useful are balancing valves with an indicator of the applied pressure drop. Make sure none of the materials used are toxic, and that they can be used with high oxygen concentrations (we simply contacted the manufacturer and their R&D checked and confirmed it). An example of a valve that also has a pressure drop indicator is IMI hydronic engineering STAD-C. Engineers at hospital Geel are also developing a 3D printed version.

At least one of these valves will have to remain completely open: at least one resistance free circuit, meaning a circuit where the ventilator's internal pressure measurement at the inspiratory and expiratory end is the same, is needed for the ventilator to work properly. This can be the circuit of the patient with the least compliant lungs.

We are aware of the fact that actual pressure regulators make for a better solution, but these are not as readily available as the proposed flow control valves.

The video below, by our team member Dr. Matthias Mergeay, was made to explain an earlier version of the circuit, only containing the control valves and one-way valves on expiratory circuit:



Instruction video for the use of flow control valves (early version of the circuit).

Connector with Luer port

To add both pressure measurement and individual capnograms for each patient, an extra Luer port will be needed. Connectors with Luer ports can be found in hospitals, can be bought through medical supply stores or could be 3D printed.

Pressure Transducer

Add a pressure transducer (pressure meter or manometer) to monitor the pressure close to the patient.

Pressure transducers can most simply be obtained from IV (intravenous) and IA (intra arterial) sets already present in hospitals, such as the transpac disposable pressure transducer. There is no need to use the flushing system in an emergency, but by flushing the system one avoids possible dampening of the measured pressure. This transducer

can then be connected to a monitor in the usual way. **Please note that you will likely have the option of setting alarms through the indivual monitors.**

In case of shortage of monitors, multiple patients can be connected to a single monitor, using the same switching system normally used to monitor multiple pressure measurements for a single patient (like ABP and CVP).

Image of the disposable pressure transducer connected through the Luer port connector.

When there are no more monitors available, use any other (disposable) manometers that can be connected to a Luer port.

HMEF filter and Optional Capnogram

Add a HMEF filter for each patient. The filter usually has a port where a capnogram can be added. These filters are commonly available in hospitals or can be bought through medical supply stores.

Optional PEEP valves

A shared PEEP can be maintained in the system without individual PEEP valves, but adding these valves on the expiratory channel of each patient would make fine tuning for each individual patient possible. **We weren't able to test this yet.**

HEPA Viral Filters

Add a viral/bacterial filter in each expiratory tube. Alternatively, a single filter could be added between the splitter/combiner and the ventilator. We're not sure, however, if the accumulated moisture in a single filter will not increase the resistance significantly over time.

These filters are available in hospitals or can be bought through medical supply stores.

Effects of adding one-way valves in the inspiration circuits

We have tested the addition of one-way valves in the inspiration circuits on a Draeger Evita 4 ventilator. Test lung A was placed in a circuit without control valve (which we found to be almost identical to a circuit with an open control valve). Test lung B was connected to a circuit with partial closure of the control valve. This means that test lung B received less flow, less volume, and less pressure in its circuit. At the end of the flow phase, when the target PIP is reached within the ventilator, this means that there is a pressure difference between the circuits of lung A and B.

In the absence of one-way valves in the inspiration circuits, this yielded a backflow from circuit A to circuit B. The measured pressure within the ventilator subsequently dropped, resulting in a renewed 'inspiration' flow towards circuit B until exhalation started. This

means that the plateau pressure at circuit B slightly and gradually increased until exhalation.

With one-way valves inserted there was no backflow possible, and therefore there was no renewed inspiration flow towards lung B.

This result might however depend on the type of ventilator used! It might thus be worthwhile to test this beforehand for a particular type or brand of ventilator.

Notes on 3D printing of components

The layers and the pores of filament printed components can become a hotbed for bacteria. Components intended for real use should therefore be printed by professional companies who can mitigate this problem through higher quality printing.

Preferred materials seem to be PET-G or PP (we're also testing this). In any case the material should allow disinfection with ethanol and it should not absorb water or moist.

Splitters: files for the 3D splitter design can be found here. We tested the splitter and this worked. The flow restrictor part are less useful, mainly because there are only two options and the patient would have to be disconnected to change the flow restriction. We're also thinking about designing a cap to close one end of the splitter.

Control valve: will be made available soon.

Luer port connector: we're looking into it.

One-way valves: we're looking into it.

Ventilator Settings

Since patients should not be able to trigger each other's breaths, the system can only operate in **mandatory ventilation mode**. Modern ventilators lacking this option can be locked out, meaning the trigger threshold should be put beyond achievable values. Since mandatory ventilation is uncomfortable, patients would likely have to be sedated.

The ventilator should be put to **pressure control** mode, with a PIP (peak inspiratory pressure) set to the pressure needed for the lowest compliance in the circuit, meaning

the highest PIP needed amongst all connected patients (see also section 'how it works'). Make sure the valve on the circuit with lowest compliance remains open; the other valves can then be adjusted as needed.

Deleterious interactions between the patient's circuits can be avoided in pressure control mode, but the pressure alarms of the ventilator have to be carefully set. E.g., when an inspiration tube becomes obstructed, the volume could be diverted to another patient's circuit. A **carefully set 'pressure high alert'** will immediately make the ventilator release this too high pressure.

Likewise, the **'low minute ventilation alarm' should also be carefully set**. This is important in case a disconnection happens in a part of the circuit behind a flow control valve that is strongly restricting the flow. In this case the disconnection alarm might not be triggered, but a carefully set low minute ventilation alarm will be.

The **allowed tidal volume should be set to the maximum**, or the alarm should be turned off.

BPM, FiO2 and I:E ratio can only be shared amongst all patients. The same goes for PEEP, unless individual PEEP valves are added on the expiratory circuits (which we have not tested yet).

Patient Matching

With this setup, **patients do not have to be matched**. Individual monitoring and control for each patient makes it possible to connect patients with a different compliance.

How it works

When the ventilator is put to pressure control mode, it will release a flow of oxygen-enriched gas in the inhalation circuit until a target pressure is reached (or PIP, peak inspiratory pressure, as measured within the ventilator), after which it releases the pressure to eventually induce exhalation. Note that, in case of multiple patients the complete circuit is larger, and therefore the needed volume to obtain the target pressure will be larger. This gas flow is subsequently guided into each patient's circuit to eventually reach a control valve.

The control valve does not directly change the actual pressure, but it rather simply restricts the flow. Given a longer time to flow the same volume would still flow past the restriction, and the resulting pressure would not be different from a non-restricted passage. However, when the pressure is released by the ventilator to start exhalation (which happens at the moment the target PIP pressure is reached within the ventilator), a restricted flow will not have had the time to maximally 'complete' and therefore the obtained pressure past the restriction will be lower.

An extra pressure transducer (pressure meter or manometer) for each patient is added and connected to a monitor. This device measures the resulting pressure close to the patient. In case there is a shortage of monitors, a switching system could be used to let the caretaker switch between the pressure curves of the different patients whose pressure transducers are connected to the same switching system and monitor. From examining the obtained pressure curves, the caretaker can finetune the pressure for each patient through using the control valve in each patient's circuit.

The target pressure on the ventilator should be set to the pressure needed for the patient with the least compliant lung in the circuit, i.e., the patient that needs the highest pressure amongst all patients. The control valves inserted in the circuits of the other patients can then be used to restrict the flow, and subsequently the pressure, by the amount needed given the compliance of each of the patient's lungs.

During the expiration phase, the expirated air of each patient then flows past a viral filter and a one-way valve. These one-way valves are avoiding any backflow between circuits. The different expiratory tubes are subsequently combined in a splitter (combiner) and the combined air flows back into the ventilator.

Advantages and disadvantages

Finally, we list the advantages and the disadvantages of our system:

Advantages:

- The pressure curve for each patient can be monitored.
- The pressure can be adjusted for each patient. Patients do not have to be matched in compliance (but they do have to share some parameters such as BPM, oxygen

enrichment, I:E ratio and possibly PEEP if no extra PEEP valves are added).

- No deleterious interactions between patient's circuits are possible if the alarms are carefully set.
- The system retains the high-pressure alarms of the ventilator.
- A disconnection signal can be ensured if carefully setting the low minute ventilation alarm.
- Consists of relatively cheap, easy to obtain or produce components.
- Does not contain electronics (apart from connection to monitor) or components that are difficult to install.
- Could be set up in advance, with closed control valves, and patients could be connected as needed.

Disadvantages:

- Only possible/safe in pressure control mode.
- Patients should not be able to trigger (each other's) breaths. Modern ventilators lacking this option can be locked out, i.e., the trigger threshold should be put beyond achievable values. Since this is uncomfortable, patients would likely have to be sedated.
- Parameters such as BPM, I:E ratio, FIO2 can only be shared. PEEP could be adjusted through individual PEEP valves, otherwise this also has to be shared.
- In case an alarm goes off at the ventilator, it might not be immediately clear which patient triggered it.
- O2 and CO2 measurements at the ventilator are not reliable. But individual capnograms can be connected on the filters proximal to the patients.
- Possible auto-PEEP.
- Possible hypercapnea.

- Increased dead space through possible longer length of cables, splitters etc. This might induce auto-PEEP and hypercapnea as mentioned above, but it could also change the temperature of the airflow etc.
- Possible need to reconfigure the complete network when a patient with compliance lower than the current lowest compliance is added (since set pressure or PIP should then be increased).
- Still contains one component that is not commonly found in a hospital, the flow control valve.

Did we miss something? Let us know in the comments below!

Thanks to Dr. Mergeay, M.D., Dr. Michiel Stiers, M.D., Dr. Janssen, M.D, Dr. Voets, M.D., all from hospital Geel, medical ventilator experts Dirk Van Nieuwenhove (Technimed) and Wim De Kimpe, and 3D printing expert Tom Vrysen. We would also like to thank *Coronadenktank*, *Jonge Academie* (The Young Academy of Belgium (Flanders)) and the complete team at hospital Geel, as well as everyone who provided us with valuable feedback.

Please contact Dr. Mergeay, hospital Geel, if you wish to use this setup in a scientific publication.

If you're an expert and you want to join forces in an international collaboration on "differential multiventilation", please introduce yourself and your expertise by sending us a quick mail: differential.multiventilation (at gmail dot com).

We're also keeping a google doc with an overview of all the 'one ventilator multiple patient' solutions we encountered so far.

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