Plumbing

Updated 7 April 2020

This page described the means by which a patient should be connected to a manual resuscitator-based ventilator. Some considerations include:

This document describes critical design requirements of the patient breathing circuit. This details a key dead space issue, which if not addressed, will result in a patient breathing in expelled CO_2 and deoxygenation fast with immediate adverse result. For a detailed primer on Breathing Circuits read **Mapleson's Breathing Systems**.

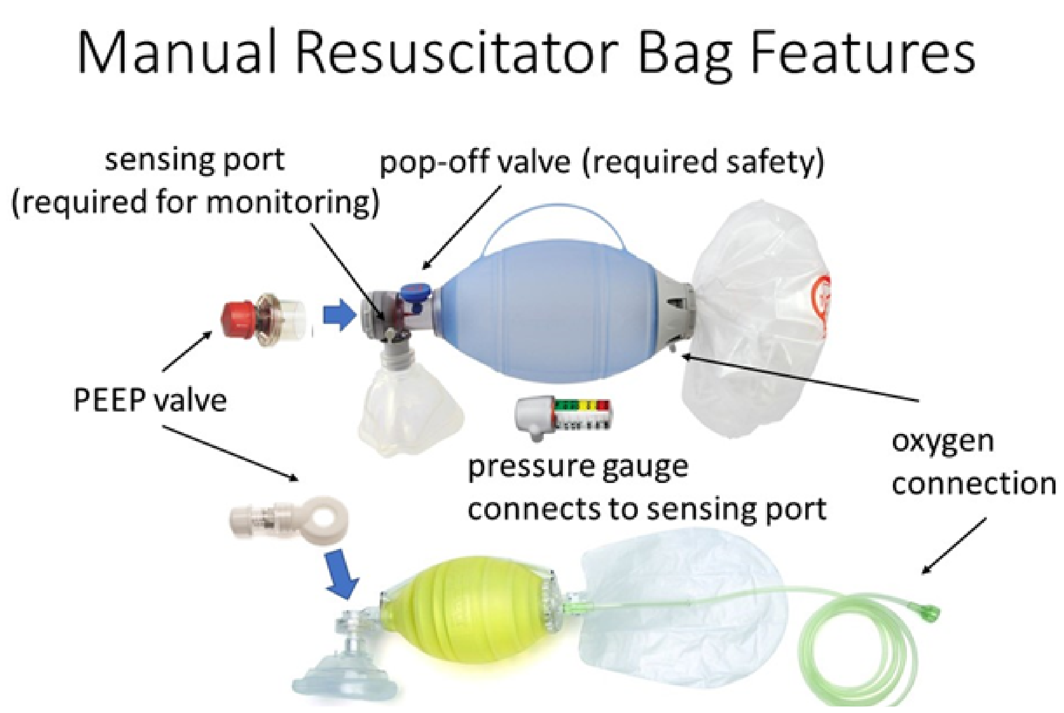
Normally, self-inflating manual resuscitators are directly connected to the patient's endotracheal tube adapter. Manual resuscitators have a "patient valve" that directs oxygen / air gas mixture into the patient and shunts the exhaled gas out to the environment. (See **Wikipedia** as a good primer on self-resuscitating manual resuscitators.) Integrated into the end bag valve mask (BVM) are a number of critical features:

- Oxygen connection and reservoir
- Pop-off valve for safety (location not important)
- One-way valve that guides air to the patient
- Exhalation valve (this stays closed while there is any pressure on the bag)
- PEEP valve that is installed post the exhalation valve and maintains backpressure
- Sensing port for manometer connection (we use this for our pressure sensor connection)

Caution: Manual resuscitator bags are in no way FDA approved for use as long-term ventilation solutions.

This page described the means by which a patient should be connected to a manual resuscitator-based ventilator. Some considerations include:

- The ventilator must be placed as close to the patient as possible.
- Bag should be secured to ventilator to prevent an awake patient from pulling on it or otherwise disengaging the bag from the mechanism. This is a fault condition that should be detected by pressure sensing.
- Care must be taken to prevent rebreathing of CO_2 due to long hoses. A fundamental challenge is the location of the one way and expiratory valves, which are typically directly integrated into the bag.



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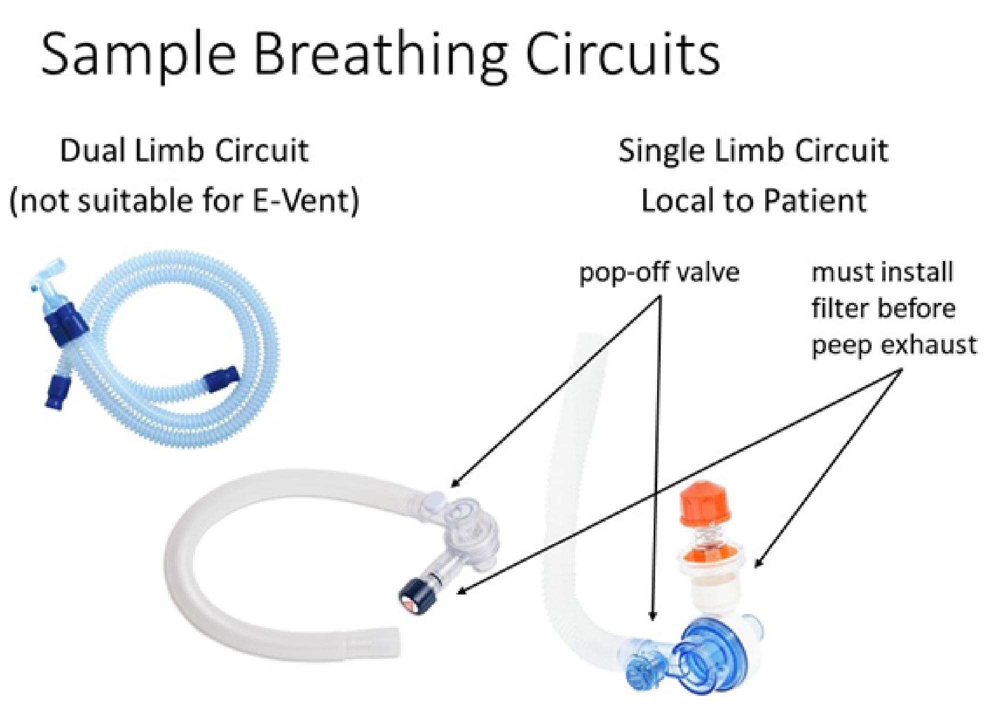
When a manual resuscitator is placed into an MIT E-Vent, or similar design, the system cannot be placed right up against the patient's head. In addition, patients need to be turned intermittently for routine care and patients can thrash and move in their beds. Even when patients are paralyzed, the paralytic may wear off at times and we must consider how to keep the patient safe from inadvertent breathing circuit disconnection or extubation. Therefore, a safe method to extend the "reach" and flexibility of the manual resuscitator to a patient lying on a hospital bed is needed. If a simple tube is used to do so, it creates a critical safety concern of "dead space."

Note: In a 1 m long tube of nominal 2 cm diameter, there is an unacceptable 314 mL dead space that the patient will breath in and out and not be oxygenated.

Dead space simply means volume in the respiratory circuit that does not participate in gas exchange in the lungs. Our natural anatomy has dead space as well. Considering gas exchange occurs at the alveoli in our lungs, every anatomical structure above it can be considered "dead space": nasal/oral passages, pharynx, larynx, trachea, and primary/secondary/tertiary bronchi. Extending the tubing through which bidirectional flow of inhaled / exhaled gas mixture occurs only increases dead space and the patient, see **Wikipedia**.

A way to move the patient valve of the manual resuscitator closer to the patient is critical in solving this issue. Standard ventilator circuits have two limbs, one for inspiration and one for expiration, so that gases can be recaptured by the ventilator. Single limb ventilator circuits with a patient valve located distally already exist on the market, but are not necessarily optimized for use with a manual resuscitator.

Note: Solving this problem requires creativity – No manual resuscitator manufacturer makes an approved solution and no manufacturer makes all the parts that will assemble together correctly.



Industry Notes

In reviewing products available on the market, we have some notes:

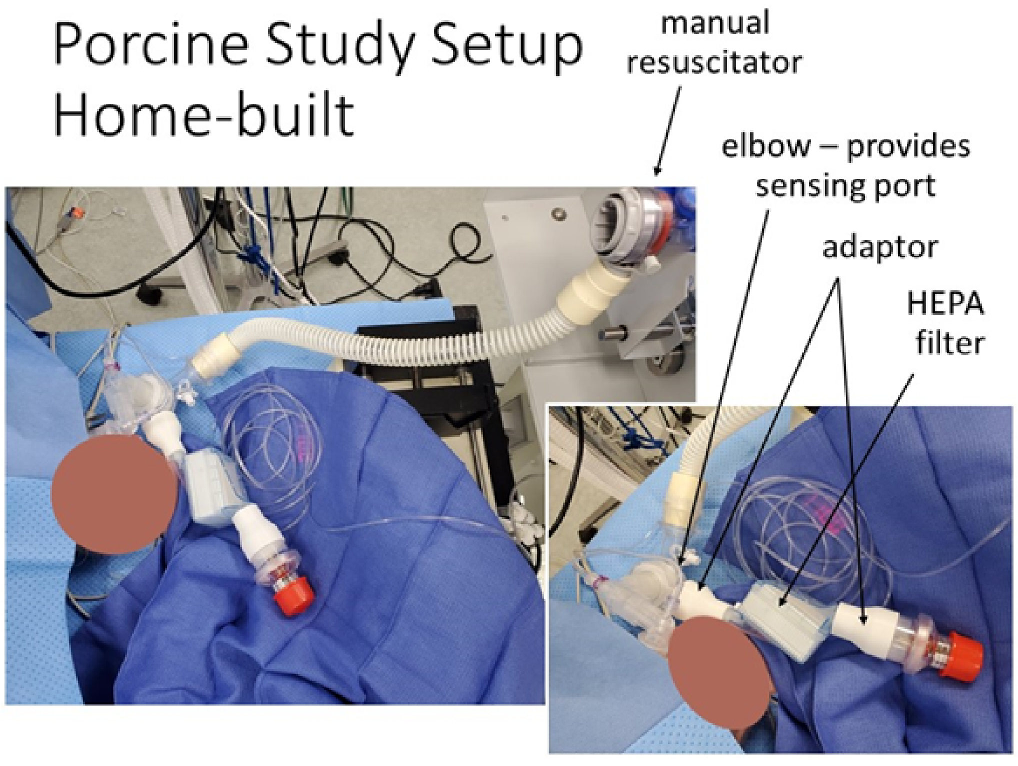
- No bag makers supply extension hoses with the appropriate fittings.
- Bags designed for reuse, i.e. autoclavable, are the only bags that can potentially survive under repeated use. We do not have any information about lifespan.
- Some Ambu bags do not have detachable heads, but they do incorporate pop-off and easily attached PEEP valves in their designs. They can only be used if extended with a separate head and extension tube. Ambu Mark 5 and Silicon Oval heads are detachable and may be available as parts. They have easily combined manometers and PEEP valves.
- Laerdal bags do have detachable heads, however in the adult sizes these heads do NOT come with pop-off valves; these are available in the Pediatric model. The pediatric model head will probably fit the adult bag.
- When a long tube is used, without a dual limb circuit and one way valving to address the dead space issue, this may affect the volume delivered to the patient; it may be necessary to increase the inspired volume.
- Addition of the HEPA filter will cause a pressure drop and may affect PEEP settings.

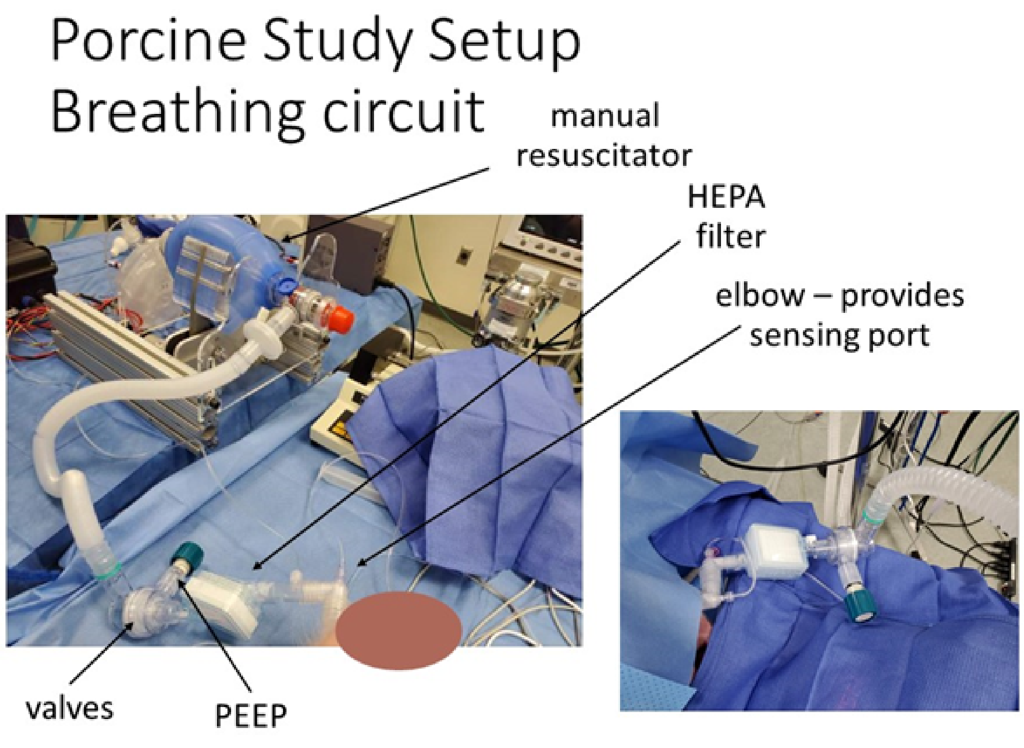
- Tightness of all connections is important.

Caution: In the worst-case scenario, placing the head as close as possible to the patient will reduce the dead space, but it is not an optimal or safe solution, especially for patients with reduced inspiratory volume.

Two version of single limb circuits are shown below. The first made use of readily available components and two printed adaptors to make them fit together, with the HEPA filter placed between the exhalation port and the PEEP. The second used a single limb breathing circuit, with most of the necessary features integrated, and a HEPA filter added inline between the porcine and the breathing circuit. This is a better position as it filters air heading both in and out of the patient, including any air that escapes from the pop-off valve. It may also help to moisten air inbound to the patient.

The best location, if you have only one filter, for it is between the endotracheal tube and the breathing circuit.





Dead Air – Additional Potential Solution

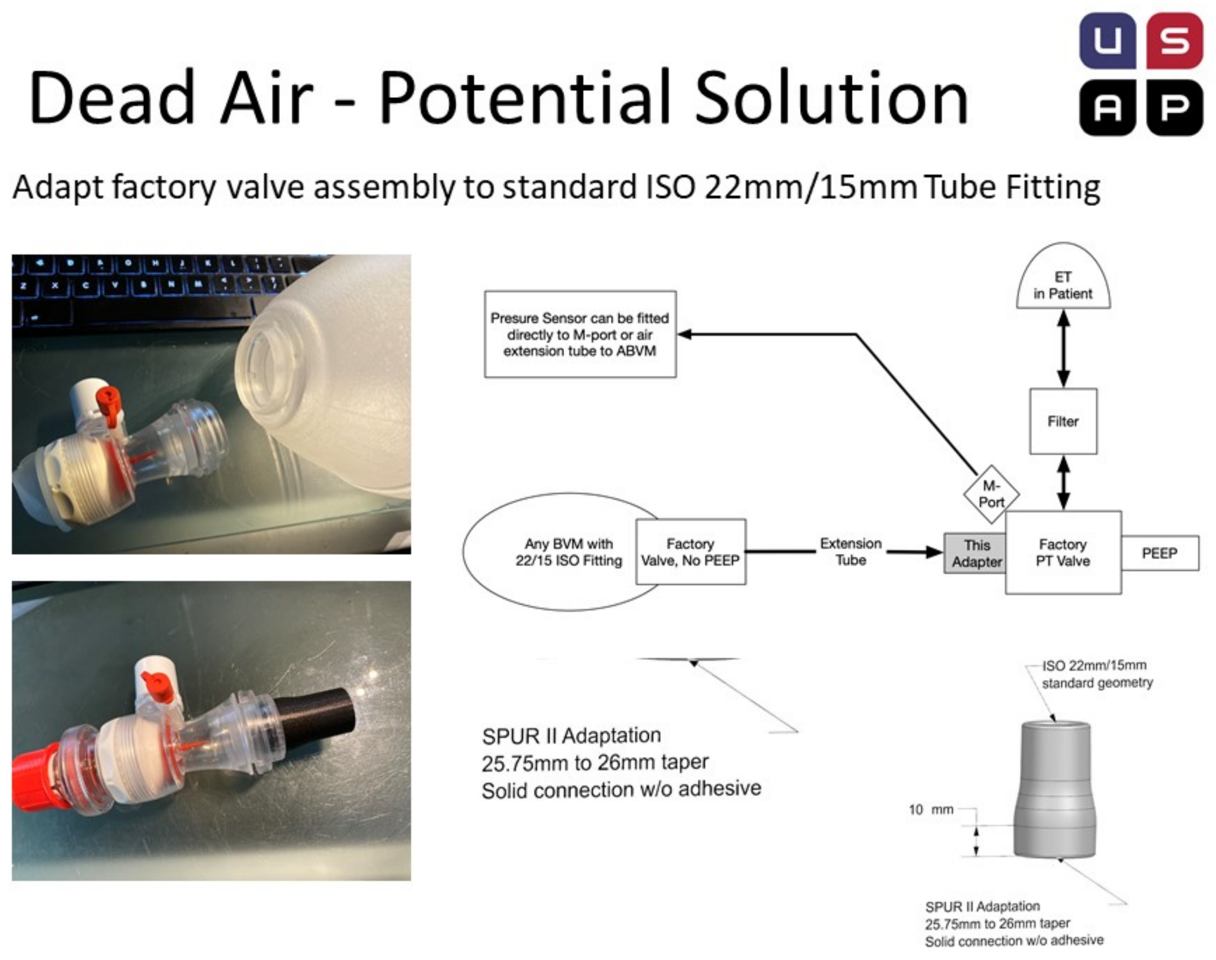
Our friends at the **US Air project**, an Oregon based group of fabricators currently scaling up, have dissembled Ambu bags and developed an adaptor, that demonstrates the feasibility of DIY circuits with a little feasibility.

Ambu has readily available complete patient valve assemblies, though limited information is available on their **website**. Ambu has readily available complete patient valve assemblies with complete valve assemblies are available for the Mk IV and Silicone Oval lines:
Mk IV Ped (w/ pop-off and Mport) #299 000 508
Silicon Oval (w pop-off and Mport) #470 000 503
The ideal solution is to order these valves, with a hasty solution being “harvesting” valves from disposable SPUR II

units. Note: Valve is not replaceable from the bag once removed. This method places the pressure port in the correct position to monitor patient airway pressure.

Connecting these valves can be accomplished with a adaptor. All Ambu valve assemblies have a conical taper from injection molding that allows for a reliable adapter connector to be quickly fabricated. This adaptor can be 3D printed (fast, but sub-optimal), CNC milled with a sub 1 min cycle (in 6061) or injection molded (**ProtoMold** quote of $1.63 in 5000 volumes, in HDPE). A hose can now be used to connect this valve to an intact manual resuscitator. The extra valve assembly on the intact manual resuscitator should be inactive for practical purposes.

Caution: Care must be taken to ensure that connections are secure. Medical grade adhesive should be used.



45 Replies to “Plumbing”

Yueh Lee 2 April 2020 at 01:12 Reply

Bingo – thanks for posting this, it is absolutely critical and unfortunately not recognized by most teams who are getting into this for the first time.

Anuruddha Tennakoon 2 April 2020 at 02:22 Reply

HME Filter?

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vikas mali 2 April 2020 at 09:03 Reply

Thanks for adding this information. Could you please check, one ventilator to be connected to multiple patient by connecting some special distributor and increasing the pumping capacity.

> **Robert M. Ellsworth** 3 April 2020 at 13:11 Reply
>
> Vikas, that won’t work for a number of reasons, most of which are connected with the fixed repetition rate of the device. This would force all the patients to breathe at a common rate, perhaps involving over- or under-oxygenation of blood gases, would cause terror and discomfort if they are suffering from the usual ARDS-syndrome problems, and would require additional safety equipment to avoid the issues already identified in preventing lung damage (particularly in necrosed or autoinflamed tissues) through excessive pressure, volume, or overly high PEEP.

A ventilator is not the same thing as a positive-pressure air support; I recommend you look at the detail-design differences between ordinary CPAP (which is 'not' a preferred bridge-ventilator conversion solution) and bilevel CPAP (which is) to see more of what a positive-pressure supply solution (pulsed or not) would involve. The E-Vent design is specifically intended to work as a substitute for full invasive 'medical ventilator' substitution, a very different technical exercise.

Alan Lichtenstein 2 April 2020 at 10:42 Reply

I spent a long time last night trying to solve the dead space problem with longer tubing to the ventilator, to enable it to be at a slightly greater distance from the patient.

Anesthesia machine ventilators solve this problem by using two one-way valves, one on the inspiratory limb, and one on the expiratory limb of the circuit. They are built into the machines, so are at a distance from the patient's endotracheal tube. For cases with the patient's bed turned, we use extensions so that the machine/ventilator is quite a long distance from the patient's endotracheal tube.

I was wondering if inexpensive one-way valves could be made (?3-D printing, or another approach) and placed just before an HME/HEPA filter on the patient's ETT using Y-tubing, similar to an anesthesia circuit. Alternatively, this could be handled by solenoid valves timed with the ventilatory cycle, but I would think patients would need neuromuscular blockade (paralysis) to avoid fighting the ventilator. You would have to fabricate a Y-piece with the appropriate sized connectors (they are standardized) containing two one-way valves, positioned one on each limb of the Y, with the flow direction opposite each other.

I would think this could solve the dead-space issue. Please someone chime in if I am missing something here.

Steve Harrington 3 April 2020 at 18:27 Reply

Another company is working on 3d printable check valves, based on the check valves in a painting respirator. It is not too hard.to make them. They don't need to seal perfectly to reduce re-breathing.
Also, your vent should have a sigh function, if possible . (hold pressure for a while to open up the lungs)
Steve Harrington, Flometrics

Kent Mcqueen 4 April 2020 at 01:54 Reply

Could you post the name of the company?

Dan Kline 5 April 2020 at 13:44 Reply

We are developing a non-invasive Respiratory Assist Device based on CPAP and BiPAP devices. We introduce oxygen and contain and filter all exhaled gas form normal breathing, cough or sneeze. We have developed simple check valves, with various cracking pressures, that use 3D printed housings and silicone valve elements cut from flat sheet. We are working on completing a video, after which I'll post the video and the models on our website at http://www.novoengineering.com. Hopefully by tonight.

Dan Kline 5 April 2020 at 13:45 Reply

Yes, we are the company that Steve from Flometrics was referring to BTW.

N H 4 April 2020 at 14:17 Reply

We do have a little pause during which we take a pressure measure. Releasing pressure on the bag causes the expiration valve to open.

Finnie Wagaman 2 April 2020 at 13:34 Reply

What about using water as the piston to pump the air? A large U shape pipe filled with water. One leg would be closed at the top with in and out check valves. This would at act as the air pump. The other leg is open at the closed at the top with in and out check valves. This would at act as the air pump. The other leg is open at the top. A displacer (not a piston) lowered into the water on the open leg provides the compression. The delta in height between water in both legs is a defined pressure. The air volume is monitored by the change in height of the pump water column.

JOHN STRUPAT 2 April 2020 at 13:52 Reply

I'm confused.
If you use a BMV valve at the patient. you effectively have a "Y" and 2 check valves in place.
The duckbill valve will not allow patient Exhalation back into the hose from the BMV.
The other valve will not allow Inspiration from the room via the PEEP control.

How is there any dead space created?

> Mitch Berkson 3 April 2020 at 01:14 Reply
>
> It looks like the issue is that there is not standard plumbing enabling a hose to be attached between the bag, which can't be too close to the patient, and the BMV valve which needs to be as close as possible to the patient.

Leah Pastel 2 April 2020 at 15:10 Reply

The tubing could be longer, if it was narrower, and still be the same dead space. Could the motor/ device handle the additional pressure?

> pavship Shipitsyn 3 April 2020 at 03:48 Reply
>
> +1
>
> N H 3 April 2020 at 11:59 Reply
>
> It is critical to eliminate dead space, not just minimize it. If not the patient will re-breathe and de-oxygenate.

jasper ayaye 3 April 2020 at 05:41 Reply

This is going to save lives especially here in africa,
we have no OPTION !!!

camilo pacheco 3 April 2020 at 06:34 Reply

EXCUSE ME I'M NOT A DOCTOR OR SOMETHING LIKE IT BUT I HAVE A LOT OF INTEREST IN DOING IT IN MY COUNTRY PEOPLE DIE IN THE STREETS AND NOBODY DOES ANYTHING, I JUST WANT TO KNOW IF SOMEONE DID IT AND TELL ME THAT THIS MECHANICAL RESPIRATOR IS PLEASANT AND GRAPHIC THIS CAMILOPACHECO123123@GMAIL.COM

Rahul Jojo 3 April 2020 at 09:51 Reply

How do you monitor and apply the inlet pressure to the patient through Inlet Valve ?

donald briner 3 April 2020 at 11:36 Reply

Here is a loose thought. How about encasing the bag in a rigid container just larger than the bag itself. Then you control the pressure inside the container to actuate the bag. The bag and container could be placed just as close to the patient as normal with a pneumatic line or two leading to the control box. It would be a bit heavier.

> N H 3 April 2020 at 11:57 Reply
>
> This has been tried, but we believe that achieving safe closed loop control is harder.

Chris Graham 3 April 2020 at 12:51 Reply

N H, what is the main difficulty with achieving safe closed-loop control with the approach suggested by donald briner? Is it difficulty with controlling the exact volumetric compression of the bag? I was thinking about a similar approach, but with an outer bag rather than a rigid container (although either could work). The (small) space between the bags would be filled with water, and additional water would be introduced to squeeze the inner bag; because water is incompressible, the volume of air squeezed out of the inner bag would be almost exactly equal to the amount of water introduced. The total water volume would be constant (a closed system), but the amount of water moved in and out could be easy and accurately controlled with a variable-stroke piston. The piston could be actuated using either compressed air/oxygen or utility water (or an electric actuator, of course), regulated to appropriate pressures.

N H 4 April 2020 at 14:24 Reply

If incompressible water is the driving fluid, then position controlling the piston position is the same challenge. If a compressible fluid is used to compress the bag, then it's better to look into a direct pressure control system that replicates many of the old electricity free vents. This presumes a pressure source, which may not be readily available in field hospitals.

Chris Graham 4 April 2020 at 20:39 Reply

N H, thanks for the response. Assuming that the purpose of position control of the piston is just to ensure than the correct volume is delivered each stroke, that could be accomplished pretty easily with adjustable hard stops for the piston, movable reed switches on the outside of the cylinder (triggered by a permanent magnet in the piston), etc. The piston can then be actuated by any pressurized fluid, such as oxygen or utility water (which typically comes in around 40 psi; since the max allowable bag pressure is about 0.5 psi, you would want a ratio of areas on each end of the piston of 80:1; this means only about 10ml of utility water would be exhausted per 800 ml breath). I assume even field hospitals, at least in the U.S., will have utility water lines run to them, although I could certainly be wrong.

In any case, this system could also be actuated with a motor, or possibly a solenoid that pushes directly on the piston. That eliminates the advantage of not having to source suitable motors, but there are other advantages as well: the sleeve could be manufactured very inexpensively and quickly by companies that make film plastic products, and it would be very compact. Also, measuring the cylinder pressure, i.e. for the purpose of sounding an alarm, gives a direct indication of the bag pressure, without having to tap the pressure sensor into the bad or airlines.

I should mention that, having looked at the various BVM designs out there, I don't see a good way (on most of them) of sealing an outer bag or box at either end of the inner bag like I suggested before. I think a better approach would be to make the outer bag double-layered, with the two layers seal-welded together around the openings at either end. The BVM bag would just be inserted into this double-walled sleeve, and water would fill the sleeve, accomplishing pretty much the same thing as before.

Jim DeLillo 3 April 2020 at 12:57 Reply

It appears that you are using a reciprocal actuator to pump the bag.
I believe this design can be simplified and more reliable by using a rotary (peristaltic action) actuator.

N H 4 April 2020 at 14:22 Reply

The reason we settled on the bag is it's ability to control volumes with some reasonable precision.

Alan Lichtenstein 3 April 2020 at 14:48 Reply

Alan Lichtenstein 3 April 2020 at 14:48 Reply

Part of the reason that the ventilator has to be at a little distance from the patient is so that if the patient turns their head (or a caregiver turns their head) the patient doesn't become accidentally extubated (their endotracheal tube is pulled out of their airway). Trust me, this is easier to do than you think. That is a potentially lethal complication in these patients. It becomes an even more difficult problem if patient's are proned.

There needs to be some length of flexible airway tubing between the patient's ETT and the ventilator.

Stephen Farrington 4 April 2020 at 11:12 Reply

Alan, can you provide us more information on the frequency with which patients are proned? I was referred to this article (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6026253/) but don't know how much the practice is being applied to COVID-19 ARDS patients with or without ventilation. Would one practice compete with the other? Thank you.

Alan Lichtenstein 4 April 2020 at 11:23 Reply

I don't practice in an ICU setting (my practice is mainly CV, general, trauma, and OB anesthesia), so I don't know the frequency that patients are proned. But with ARDS it is known to be helpful in many patients, and critical care physicians and anesthesiologists are well versed in proning patients. Anecdotally, it is being used with some frequency in COVID-19 patients on ventilators. As the article in Chest you referenced indicates, clinical trials have been difficult with ARDS patients – it's hard to get clean data, and the results have been mixed.

To quote the paper, "prone positioning moves from a salvage therapy for refractory hypoxemia to an upfront lung-protective strategy intended to improve survival in severe ARDS. Indeed, prone positioning has never been proved to afford a survival benefit when used as a late rescue therapy for refractory hypoxemia." I think this lesson has been learned by intensivists – hence the push for early proning in ARDS patients, and COVID-19 patients.

I'm really drifting from my specific area of expertise. Hopefully there is an intensivist on this group who can provide a more definitive answer. And I don't know about proning patients on CPAP or humidified high flow nasal cannulas. Personally, I've not seen it. But these are different times we now find ourselves in.

Puiu Craciunescu 4 April 2020 at 00:13 Reply

Hello! I'm confused about calculating the volume of air we have to deliver to the lungs. If, for example, the required air volume is considered 400ml at atmospheric pressure then it is found as a volume of 200ml at 40H2O pressure (for example). Even so a normalized volume calculation could be made at atmospheric pressure (p1V1 = p2V2) but we should be able to approximate lung volume.

Brian Foster 4 April 2020 at 01:59 Reply

How close do you think you may be to a workable design (I.e. not necessarily the final design but a first version that could be revised in a second round)? The reason I ask is the COVID19 wave will begin peaking in the US in just a couple of weeks. It is possible to have teams (First Robotics team mentors and various businesses) make component parts for delivery to MIT for assembly. We would do this at likely no cost. If a workable design is produced, the production and assembly could start almost immediately and complete units could be sent to states and foreign governments as needed. Each completed unit is worth perhaps two or more lives.

Stephen Farrington 4 April 2020 at 11:15 Reply

I second this question. Both my company and my FIRST robotics team could contribute to production (while maintaining strict social isolation and disinfection procedures) when the time is right. Is it possible to release a preliminary bill of materials to facilitate planning and preparation?

miguel hernandez 4 April 2020 at 03:59 Reply

Si se encamisara otro tubo mas pequeño dentro del que se introduce en la traquia y por medio de una segunda vejiga se extrae el CO2 y se diseñan pequeñas válvulas periféricas en las extremidades de los tubos tendriamos dos vias en una evitando el espacio muerto, espero sus comentarios

Frank Ha 4 April 2020 at 04:27 Reply

Cool stuff guys! However, I am a little confused. In the beginning, it is said that manual resuscitators are connected to ETT. Then, further down the article, you guys talked about issues concerning the use of a mask and single-limb tubing.

Does this mean that if I have dual limb tubing for ET, I shouldn't have to worry about plumbing and dead space issues?

N H 4 April 2020 at 14:20 Reply

The dual limb is used with a machine that controls both in and out, which is needed with anesthesia gases. With the bag there is only one way flow to a patient, hence a single limb.

miguel hernandez 4 April 2020 at 04:41 Reply

¡¡Ya tengo la concepción de las vavulas para los tubos encamisados!!

4 April 2020 at 11:14 Reply

There are two ways to fix this.
You can use a dual limb or a single limb both will work.

In a dual limb you need an inspiratory and expiratory limb and a wye. What most people are forgetting is there is a continuous flush of oxygen. From the bag valve mask (bvm).
That eliminates the rebreathing on the inspiratory limb, the wye attaches to the patient via a flex tube, and the expiratory allows u to attach a filter at the end for filtration. This is usually done on almost all ventilators

The second way is to use a single limb circuit, and use a one way valve near the patients flex tube, this prevents rebreathing and a continuous flush from the oxygen

Both works co2 rebreathing is not an issue

4 April 2020 at 11:17 Reply

In fact the second method is often done when patients needs to go for an mri as a ventilator is not able to enter into an mri area

The second method is also done so that when on a ventilator a patient when cuff deflated allows for speech

Jeremy Yew 4 April 2020 at 11:31 Reply

This method requires a t piece as well to allow for exhalation

Frederick Pfleger 4 April 2020 at 12:16 Reply

I have concerns about using a HEPA filter on the exhaust. We use in line HEPA filters in Pharma production but often experience problems due to the filters plugging up and creating a significant increase in backpressure.
An idea since we want a specific backpressure in inches of water is to simply use a water column. If a tube is connected to the discharge and the tube placed in a container with a predetermined height of fluid the discharge air would percolate thru the fluid. If the fluid were a disinfecting solution it could be used to control both the backpressure and decontaminate the discharged air. If the clinician wanted to adjust the backpressure, they could just adjust the fluid column height.

Cesar Gallardo 5 April 2020 at 12:05 Reply

What if the bag is surrounded by a self-expandable net (some lines with little springs) and inside a small case, just big enough to fit the bag. Then the torque to press the bag is exerted by a single line, similar to a bike brake. This way all mechanical-electrical gear can be as far as needed, and the bag as closest to the patient as possible reducing dead space. This way it is only needed for the case to be fixed in a way torque is correctly transmitted (speaking out of total ignorance here, but the bag could even be attached to the patient's forehead and move with him/her).

Dave Reyner 5 April 2020 at 17:16 Reply

Greetings,

For my project I mocked up setting the Fi02 using venturi plugs and a standard parts. It's a kitchen counter mock up, so please forgive the masking tape and "plug" analog. https://photos.app.goo.gl/yPmgS7QcQayEHpox5

Good luck, Dave

Shiro Yoshida 5 April 2020 at 20:33 Reply

Can we apply the numerical analysis technique of
Smoothed Particle Hydrodynamics (SPH) for the efficiency verification
of this equipment as a whole?

DHANUSH A 6 April 2020 at 01:08 Reply

Greetings,
I am from India, Here a lot of agencies NGO and govt organizations are working and releasing several models of ventilators, but I found MIT Event is certainly differ from all mechanical replacements, Really a clinically proven design, Hope you have a successful design now, will u release a BOM and technical details of the same as a document in this registered group of members, if so we like peoples also can develop the same as a model and contribute our suggestions for your consideration. We are an embedded systems design lab and very much interested in this concept. with your permission we would like to be a part of this project and like to work together for a better world.
availability of parts, design logic, assembly methods etc are helopful.
We have already developed a mechanical model with gear wheel mechanisms, but clinical aspects are not great with that design,
hope to hear from u the best.

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niraj hirani 6 April 2020 at 13:54 Reply

Hi, I believe it is important to create a diverter on the expiratory valve of the ambubag and send it through an inline expiratory filter before releasing it into the air, SARS COV2 is airborne, and can easily contaminate the ambient environment.
or alternatively, remove the valve assembly from the ambubag(you need an ambubag which can do this) and replace it with a one way valve, use a double circuit ventilator tube with a Y tube connector, with a separate expiratory valve and filter plus PEEP valve on the expiratory side.

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COMMENT

Post Comment

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