



# An open-source powered and ergonomic personal protective respirator for frontline COVID-19 response



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## ABSTRACT

Intending to shield front-liners who are currently exposed to COVID-19, and because of the lack of proper powered air-purifying respirator, this study shows the design and development of an open-source ergonomic respirator with a washable filter. This device has an estimated working time of 12 h, and the tests' airflow always showed a value over 4.5 cubic feet per minute, a higher value than the national institute for occupational safety and health specification for full-face closed respirators. The proposal relies on 3D printing technology for all the custom-design parts and usages easy-to-access components for the rest of the material. The mask for the APRPAPR in the article has a defogging feature, 180 degrees of viewing angle, an ergonomic profile, and no obstruction on the mouth to show the user's full face. This respirator has an estimated cost of 318 USD, approximately one-third of the market's price of well-known brands.

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## Specifications table

Hardware name	<i>Personal Protective Respirator</i>
Subject area	Medical
Hardware type	Personal Protective Equipment
Open Source License	CERN Open Hardware License v2
Cost of Hardware	USD 318
Source File Repository	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>

## Hardware in context

The year 2020 has been historical where the entire world suddenly stopped due to a respiratory disease, SARS-CoV2 virus, or commonly known as COVID-19. This virus is spread through respiratory droplets and aerosols when an infected person coughs, sneezes, shouts, or talks. For this reason, the usage of face masks and respiratory PEPPE (personal protective equipment) has been in high demand on every corner of the globe. However, the sudden massive need for PEPPE has overpassed

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the manufacturing capacity of the suppliers [1,2], affecting principally health and frontline workers because they have no other option than to take care of patients even with a higher personal risk or without sufficient equipment. Nevertheless, all the face masks and gloves are mainly thought to prevent the virus's spread instead of the user's safety. This key fact leaves all frontline and health workers exposed to the pandemic, even with the corresponding equipment. A shocking example was Italy, a country which, at one month of the pandemic, had already lost 150 doctors and 40 nurses [3]. In the other side of the globe, in the U.S., by the end of the year 2020, almost three thousand health care workers died from COVID-19 [4]; and, Mexico have lost over one thousand doctors by September of 2020 [5] and above 4,000 health-workers deaths by the middle of year 2021 [6]. Nonetheless, one year and a half has passed on pandemic and vaccines distribution is starting to bring hope. Yet, only in the U.S. the cumulative cases go above 32 million, and more than 330 new cases were reported by May 11 [7]. From these numbers, it is reported than half a million were healthcare personnel cases [8], highlighting the importance of providing the proper equipment. On the other side, Mexico is now fortune of having a death percentage close to zero for healthcare workers, which shows how critical it was to shield frontliners [6].

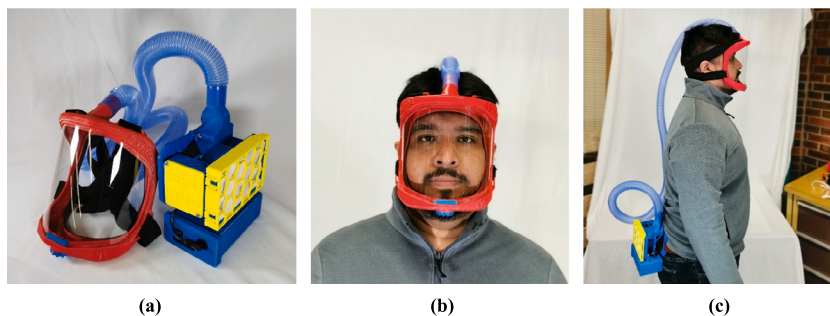
This awkward situation forced front-liners to improvise with different PEPPE types and even adapted some from other application areas, like snorkel masks and industrial equipment [8–10]. These clever proposals are dedicated to respirators, one of the few pieces of equipment that shield the user instead of preventing the virus's spread. However, most of the proposed respirators have focused on passive filters, which usually have restricted airflow; only a few suggest an powered respirator [11]. Understanding this historical event of COVID-19 and considering the critical need for protective equipment that covers all the requirements of front-liners, an open-source powered filter and ergonomic respirator was developed with the pure intention of shielding health care workers.

## Hardware description

Looking to support health care workers and provide an emergency solution, this article shares the design and development for a personal powered ergonomic respirator with a filter, shown in Fig. 1. The respirator uses an air blower which continuously push air through a A95 filter and conducts the clean air through a CPAP (continuous positive airway pressure) hose. The pipe connects and provides a positive pressure into a closed chamber mask, forcing the wearer to inhale clean air. In the chamber of the mask the exhaust air is released directly to the environment through a one-way valve. This constant air flow is the great advantage of the powered device which in contrast to passive respirators the user must rely on its own lungs and breath to acquire clean air. The APRPAPR (powered air-purifying respirator) has an ergonomic full-face mask with a defogging feature and without any mouth obstruction, so the user's face can be visible. Plus, the gear weighs only 2 kg, and it is belted to the back of the user so that the front-liners could have free hands for any task. The airflow is constant and over 4.5 CFMs (cubic feet per minute) with a battery life span of 12 h.

Additionally, the authors tested this device for airflow in the face chamber in a stochastic way and concluded it to be comfortable. The respirator was used for 8 h with no lack of air at any time, and even quick runs and jumps were done but no air scarcity was felt by the authors. However, the respirator's voltage can be regulated for even better airflow requirements. It is also important to note that the battery time is directly linked with the airflow speed. Some of the other noticeable characteristics of the proposed respirator include reconfigurability, maintainability, and quick-&-easy replacement of filter and battery.

This device employs 3D printing technology (additive manufacturing) for the dedicated parts and considers simple out-of-the-shelf components for the rest. The respirator was designed in SolidWorks® 2019, and the 3D models are shared in format STEP AP214 for a straightforward and open-source adaptation. If the replicators desire to customize the mask in size or share, they are open to doing it. Alternatively, on the other hand, the battery holder can be adapted for the local source. The respirator is modular so that even the filter can be updated for the user's best or match international regulations.



**Fig. 1.** Powered and ergonomic respirator (PAPR) for front-liners. a) Full assembly of PAPR, b) front view of respirator showing the open face, and c) side view of PAPR on user.

## Development

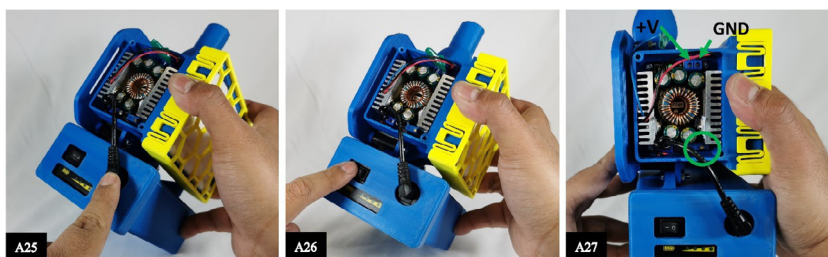
This study's respirator took numerous iterations before reaching the final design, as shown in Fig. 2. Selecting the right components for filtering was one of the most critical milestones in the respirator design process. Understanding the need of front-liners for carrying the PPE around 12 h and seeing the shortages on the disposable equipment, the A95 filter from ACAMP Inc. was chosen as filter media. This filter has the ability to be washable, holds particles similarly to N95 filters, and the company states a life cycle of 1 month per filter, meaning that our respirator will have long intervals between expendables. However, as the filter lead time was taking weeks, designs were tested to understand the device's behavior. As shown in Fig. 2-a and 2-c, some of the first prototypes were using fans of 40 mm and 120 mm in size, being the last one the first version to reach 4 CFMs. However, this version was using a facemask as filter media, and once the A95 was at disposition, the respirator was lacking pressure, and not even 1 CFM came from the device, Fig. 2-b. In an intent to overcome this pressure drop, multiple fans in series were combined, see Fig. 2-d, but no combination gives a better airflow than 1.5 CFMs.

Additionally, the prototype becomes excessively voluptuous and uncomfortable for the user. This situation was originated from the high density of the A95 filter, and the type of fan had to change to overcome this pressure drop. The change was from axial fans to centrifugal compressors, well known as air blowers, which have the characteristic of providing a high-pressure airflow.

Additionally, one important feature in the development of the respirator was to design a proper mask. Other designs and authors used snorkel masks or even breathing apparatus for different purposes, which can be acceptable for emergencies. However, as frontline work shifts from ten to twelve hours, wearing these masks makes them uncomfortable and brings some issues such as fogging, excessive heat in the mask chamber, and limited vision angle. Therefore, a proper ergonomic mask was developed to cover the need of front-liners. With the help of a 3D scan, a human face was taken as a reference for this development. As shown in Fig. 3, the first step was to model an ergonomic frame for the mask's possible contour.



**Fig. 2.** Prototype iterations of main gear. a) 120 mm fan prototype with face mask filter, b) 120 mm fan prototype with ACAM filter, c) 40 mm fan with face mask filter, d) prototype with 4 equal fans in series, and e) prototype with air blower.



**Fig. 3.** Mask Development process. a) initial ergonomic frame, b) first mask design clamping below the jaw, and c) final design with improvements from previous iteration.

A design and prototype of the first mask were then implemented, and informal feedback was collected from users. Finally, with the enhancements taken into consideration, a newer version of the mask was designed, which includes an angle vision of 180 degrees, an exhaust port to allow proper airflow, and has defogging features thanks to the air hitting the screen of the user.

Moreover, the ergonomic contour unfortunately will not cover all users because the shape and form of faces varies from person to person. The mask was quickly tested with the authors, but it might not fit on a person with a narrower and longer face than the initial reference. Similarly, female user could have this concern as the genetics commonly shapes smaller heads for them. Yet, once a cushion and flexible band for the mask is developed in the future, this concern could be eliminated.

### Design files

Design file name	File type	Open source license	Location of the file
Respirator Mask	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Gear Body	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Filter Cover	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Battery Holder	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Battery Cover	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Belt Support	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Voltage Regulator Cover	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Exhaust Port Cover	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Screen Lock	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Gaskets	CAD	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>
Screen Cutout Pattern	Draft	CERN Open Hardware License v2	<a href="https://doi.org/10.17632/w6dcp428yv.1">https://doi.org/10.17632/w6dcp428yv.1</a>

All components were designed in SolidWorks® 2019, but all the components are shared in format STEP AP214 and S.T.L. The STL files are ready to print, and the STEP file is shared if anybody desires to implement a different component like filter or battery.

*Respirator Mask* – Contains one body for the main mask, which is ready to print.

*Gear Body* – Contains one body, the main gear where the blower, gaskets, voltage regulator, and filter are mounted.

*Filter Cover* – Contains one body, the filter cover, which helps to protect the filter and hold it in place.

*Battery Holder* – Contains one body, the holder for the battery, which is mounted and goes below the gear body.

*Battery Cover* – Contains one body, the covert that holds the battery in place and prevents to put the battery in the wrong direction.

*Belt Support* – Contains one body support that mounts on the air blower and helps to wear the respirator with a belt.

*Voltage Regulator Cover* – Contains one body, the cover for the voltage regulator that prevents any modifications to the setup of the airflow.


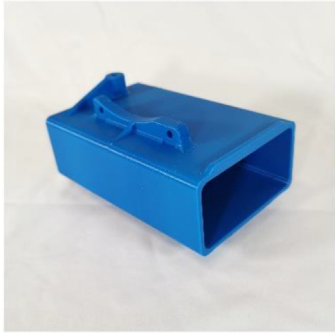


*Exhaust Port Cover* – Contains one body cover that prevents any external material from obstructing the exhaust port.

*Screen Lock* – Contains one boy lock that helps to hold the screen in place of the mask.

*Gaskets* – Contains two bodies, the square gasket and circular gaskets that seal the air blower with the main body.

*Screen Cutout Pattern* – Contains one draft for the cutout of the clear transparent screen of the mask.

**Bill of materials**

Designator/Image	Component	Number	Cost per unit - currency (USD)	Total cost - Currency (USD)
	Respirator Mask <i>Main mask body to hold the protective screen, exhaust port, and CPAP hose.</i>	1	\$ 63.31	\$ 63.31
	Battery Holder <i>Body connected to the bottom of the active gear made to hold the battery.</i>	1	\$ 32.87	\$ 32.87
	Battery Cover <i>Cover with a specific pattern for the battery and quick release spring locks.</i>	1	\$ 8.11	\$ 8.11
	Belt Support <i>Support for the active gear that allows the usage of a belt.</i>	1	\$ 19.59	\$ 19.59

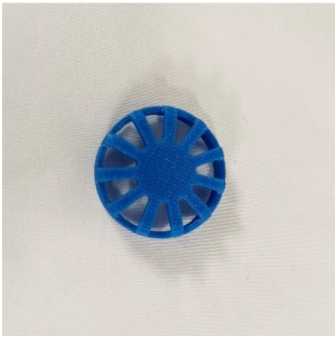
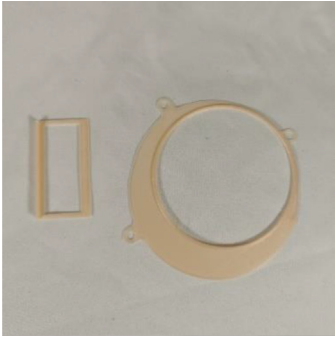
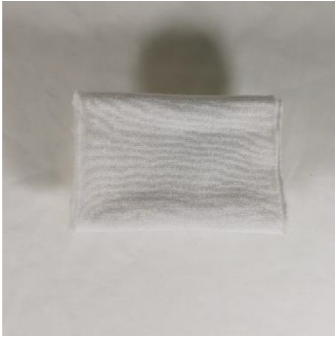

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**Bill of materials** (continued)

Designator/Image	Component	Number	Cost per unit - currency (USD)	Total cost - Currency (USD)
	<b>Gear Body</b> <i>Main body of the active gear were the filter, battery holder, voltage regulator and other components are mounted.</i>	1	\$ 43.42	\$ 43.42
	<b>Filter Cover</b> <i>Cover for the A95 filter which helps to hold the part in place and has quick release spring locks.</i>	1	\$ 15.80	\$ 15.80
	<b>Voltage Regulator Cover</b> <i>Cover for the voltage regulator to prevent any change or disturbance in the electronic.</i>	1	\$ 4.01	\$ 4.01
	<b>Screen Lock</b> <i>Lock for the screen mask which holds in place the protective screen.</i>	1	\$ 1.40	\$ 1.40


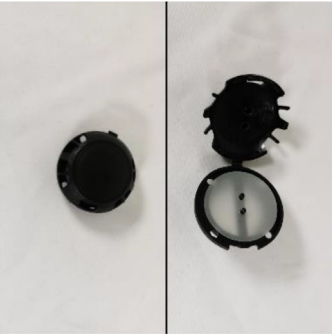
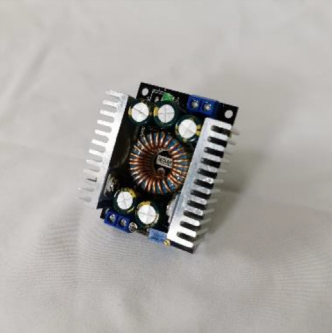



**Bill of materials** (continued)

Designator/Image	Component	Number	Cost per unit - currency (USD)	Total cost - Currency (USD)
	Exhaust Port Cover <i>Exhaust port cover which protect the flexible film from any debris.</i>	1	\$ 3.20	\$ 3.20
	TPU Gaskets <i>Gaskets for the blower inlet and outlet ports to avoid any droplet getting into the air circuit.</i>	1	\$ 3	\$ 3
	A95 Filter <i>Filter provided by ACAMP and capable of retain COVID-19 particles.</i>	1	\$ 10.00	\$ 10.00
	Mask Screen <i>Clear protective screen for the front of the mask respirator.</i>	1	\$ 5.24	\$ 5.24

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**Bill of materials** (continued)

Designator/Image	Component	Number	Cost per unit - currency (USD)	Total cost - Currency (USD)
	Neoprene Strap <i>Neoprene strap with adhesive on one side used on all the contour of the mask and prevent any damage in the skin.</i>	1	1	1
	Exhaust Port Film <i>Flexible film that provides the one way valve function of the exhaust port.</i>	1	1	1
	Voltage Regulator <i>Electronic regulator for the adjustment of the air flow and current consumption.</i>	1	\$ 15.19	\$ 15.19
	Flexible Straps <i>Flexible straps for the mask respirator which help to hold the respirator on the head of the user.</i>	4	\$ 1.00	\$ 4.00

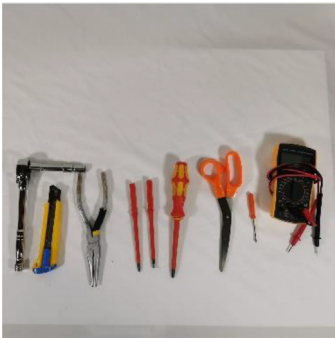



## Bill of materials (continued)

Designator/Image	Component	Number	Cost per unit - currency (USD)	Total cost - Currency (USD)
	12 Volts Battery <i>Battery of 12 V and 11,000 mAh.</i>	1	\$ 77.99	\$ 77.99
	Air Blower BCB1012UH <i>Air blower with variable voltage input.</i>	1	\$ 51.87	\$ 51.87
	12 V Wire <i>12 V wire for quick connection between battery and voltage regulator.</i>	1	\$ 1.99	\$ 1.99
	Bi-Level CPAP System RT219 <i>Hose used to connect the active gear and the mask respirators.</i>	1	\$ 42.50	\$ 42.50

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Bill of materials (continued)

Designator/Image	Component	Number	Cost per unit - currency (USD)	Total cost - Currency (USD)
	Tools	1	N/A	N/A
	Fasteners	1	N/A	N/A

The price shown for all 3D printed components is an estimation of each of their filaments and support. No technician cost is included assuming the user reproduces this device will make it for itself. The 3D printers used in the development of this study were Stratasys uPrint SE Plus and Stratasys F370, but any other printer could work as long as it has a working area above 240 mm and two nozzles to handle the dissolvable materials. Plus, the filter and battery cover should be printed with the spring locks facing the build plate; this is critical to maintaining the springs' mechanical properties thanks to the printing path. Also, the fasteners are not included in the bill of materials as the price can be neglectable, nor the cost of the tools, assuming that the user aiming to reproduce the PAPR already has them. Further information for the bill of material can be found in the [supplementary file "Respirator\\_Bill\\_Of\\_Material."](#)

Build instructions

The following instructions will guide any user to fully assemble the proposed respirator (PAPR) in this article. First, take a #8-32 hexagonal nut and locate it in the battery holder's internal figure, as shown in . Once the nut is fixed in the cavity, mount the gear body on top of the battery holder and screw the vertical bolt, leaving the fastener with some looseness, [Figs. 4-A02](#). Later, without releasing the bodies, the two 8-32 × 3/4 bolts connect the bottom flange, as shown in [Figs. 4-A03](#).



Fig. 4. Assembly instructions from steps 1 to 3. A01: insert the #8-32 nut inside the figure of the battery holder, A02: screw the vertical bolt, A03: Place two #8-32 × 3/4 bolts in the union of the battery holder and the gear body.

Manually position a nut on each of the just installed bolts and, with the help of a screwdriver and ratchet handle, tight all the fasteners, [Figs. 5](#). It is essential to distribute the load and confirm a progressive tightening on each bolt while avoiding single tightening, [Figs. 5-A05](#). Next, it is vital to install the gear body's square gasket, shown in [Figs. 5-A06](#), and keep the flange inwards the body. Otherwise, it will be impossible to access this location, and the blower will have air leakage in this area.

Mount the circular gasket in the gear body using the locating circle and mounting holes, [Figs. 6-A07](#). Pass the wires from the blower through the hole in the middle of the square Figure; see [Figs. 6-A08](#) for clarification. While holding the wire, locate the blower on the square port and mounting holes. It should be impossible to install the blower backward, but confirm the label is facing you while installing the equipment, see [Figs. 6-A09](#).

Roughly measure 7 cm from the edge of the printed body and cut the electric wire with pliers, [Figs. 7-A10](#). Peel the red and the black wires with enough metal showing for the electric connection, and cover with electric tape the remaining cable, depending on the year of the blower model, it can change in color, but it is usually blue, [Figs. 7-A11](#). Cut the 12 V connector in half or with at least 12 cm of cable, [Figs. 7-A12](#).

Make a stop knot with the main cable while leaving 2 cm of wire on the open end of the knot. Like the previous wires, peel both cables and leave enough metal showing for the electric connection, [Figs. 8-A13](#). Bring the voltage regulator and make the electrical connection of all the cables. The regulator's input must be attached to the 12 V wire, and the output should go to the electric blower. In both cases, the red cable must go into the positive terminal and the black into the negative one, [Figs. 8-A14](#). Use a small flat screwdriver and apply manual torque to each of the joints. With the regulator now connected, place the electric board in the gear body's rectangular cavity and place the #4-40  $\times$  3/8 bolts on each corner of the board, see [Figs. 8-A15](#). This operation can be done manually or with the aid of a magnetized screwdriver.

With the help of a needle nose plier and a proper screwdriver, locate a #4-40 nut behind each bolt of the regulator board, tighten all the fasteners with a distributed load, and avoid single tightening, see [Figs. 9-A16](#). Next, mount the belt support on top of the electric blower while locating all the bodies' bolts. Three #8-32  $\times$  1 $\frac{1}{2}$  and one #8-32  $\times$   $\frac{3}{4}$  bolts are required, [Figs. 9-A17](#). Like the previous operation, use a needle nose plier to position a #8-32 nut behind each bolt and tighten all the fasteners with proper distribution, see [Figs. 9-A18](#).

Put the filter in the gear body cavity and do not leave any air gaps, [Figs. 10-A19](#). Start mounting the filter cover by the right flange from the gear body, [Figs. 10-A20](#), and push the other end until the sprint locks click and the cover is flush with the filter, [Figs. 10-A21](#).

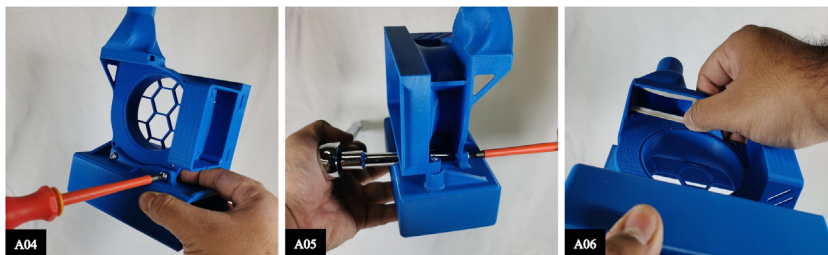
Slide the battery into the holder like shown on [Figs. 11-A22](#), and keep the correct orientation of the ports, the turn-on bottom must be in your left. This pattern helps the user to confirm if the battery was inserted correctly and works like a poka-yoke. Start mounting the filter cover by the top flange from the battery holder, [Figs. 11-A23](#), and push the other end until the sprint locks click and the cover is flush with the battery, [Figs. 11-A24](#).

Connect the 12 V wire on the battery as shown on [Figs. 12-A25](#), and turn on the battery, [Figs. 12-A25](#). While holding the gear with the voltage regulator facing you, use a multimeter to measure the voltage in the output terminals and use the regulator screw to set a voltage of 6.57 V; see [Figs. 12-A27](#) for clarification.

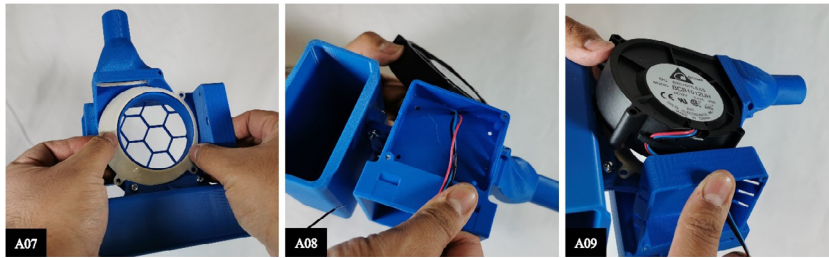
Once the output voltage is calibrated, the cover of the regulator can be installed. For that, two #6  $\times$   $\frac{1}{2}$  screws are used. Before tightening the fasteners, it is essential to keep the knot inside the container to prevent any disconnection from the electric board, see [Figs. 13-A28](#). With this step, the main gear is ready, and it should look as in [Fig. 13](#). The mask and the pipe need to be prepared.

The mask's screen can be taken from any protective equipment as long as it is clear and has a thickness of 2 mm. Once the screen is selected, we should position the pattern reference on top and use masking or electric tape to fix it to the screen, [Figs. 14-A29](#). The pattern shown in [Fig. 14](#) was made from an aluminum sheet, but standard paper can work perfectly. Once our reference is ready, we should take a cutter and mark all the pattern's contour on our clear screen, [Figs. 14-A30](#). Then, remove the reference and cut the patter with heavy-duty scissors, see [Figs. 14-A31](#).

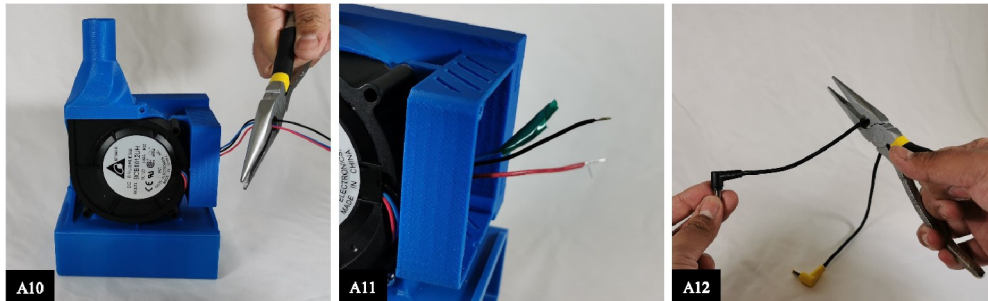
We will take the film from the facemask port and place it in our exhaust cover, see [Figs. 15-A32](#). Confirm the pins from the exhaust cover match with the holes of the mask, [Figs. 15-A33](#). If the printing quality is not good, we could use a cutter to remove excess material. Push the cover on the mask and make it fit with hand pressure, [Figs. 15-A34](#).



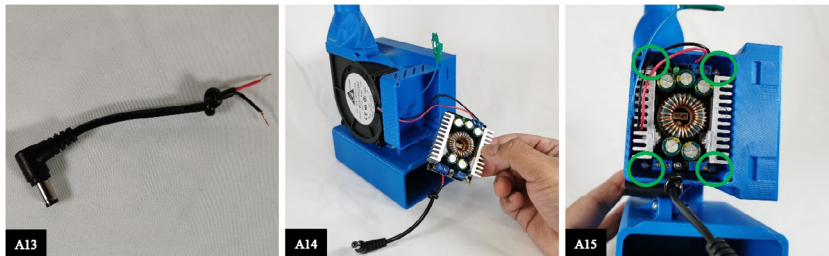
**Fig. 5.** Assembly instructions from steps 4 to 6. A04: position manually a nut behind every bolt, A05: tight all the fasteners evenly, A06: place the square gasket inside the gear body.



**Fig. 6.** Assembly instructions from steps 7 to 9. A07: Place the blower gasket, A08: pass the wires from the blower through the voltage regulator cavity, A09: mount the air blower in the main body.



**Fig. 7.** Assembly instructions from steps 10 to 12. A10: cut the cables at 7 cm from the body, A08: peel the terminals and isolate the blue wire, A08: cut on half the 12 V connector. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



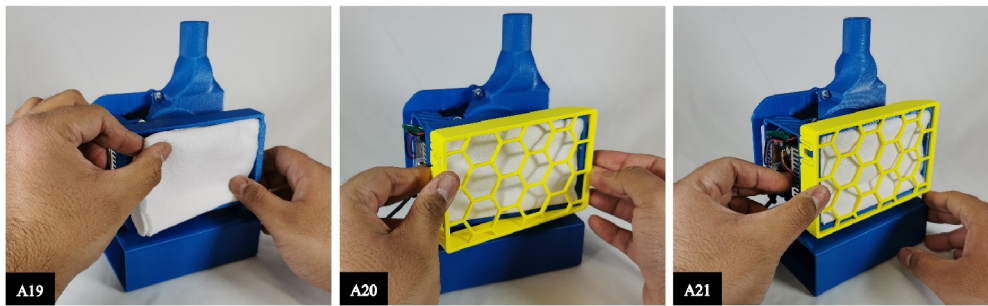
**Fig. 8.** Assembly instructions from steps 13 to 15. A13: make a stop knot on the 12 V cable and peel the wires, A14: connect all the cables to the terminals of the voltage regulator, A15: position the electronic board in the gear body.



**Fig. 9.** Assembly instructions from steps 16 to 18. A16: tight evenly the fasteners of needed for the voltage regulator, A17: mount the belt support behind the air blower and put the fasteners in the joints, A18: install nuts on every bolt and tight all the fasteners evenly.

To install the screen in our mask; first, we need to remove any protective film it might have. Then, insert the screen on one side of the mask within the side flanges, [Figs. 16-A35](#), and start to slide the transparent sheet along all the mask's top flange, [Figs. 16-A36](#). Finish the installation by inserting the clear screen on the opposite side of the mask and hold it with your hand, [Figs. 16-A37](#).





**Fig. 10.** Assembly instructions from steps 19 to 21. A19: install the filter in the main cavity, A20: mount the filter cover beginning with the holding flange, A21: finish the mounting of the filter cover by clamping the spring locks.



**Fig. 11.** Assembly instructions from steps 22 to 24. A22: Slide the battery in its holder, A23: start installing the battery cover with the top flange, and A24: finish the clamping securing the spring locks.

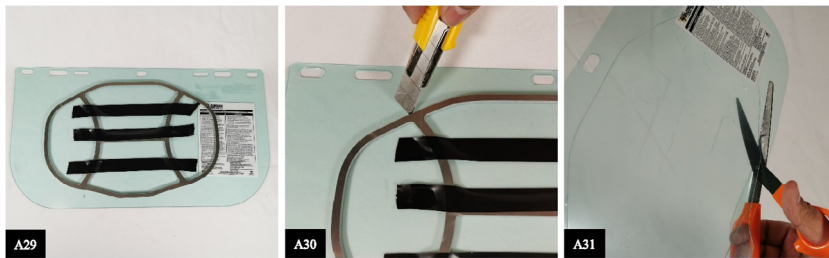


**Fig. 12.** Assembly instructions from steps 25 to 27. A25: connect the 12 V wire on the battery, A26: turn on the battery, and A27: regulate the output of the electric board to 6.57 V.



**Fig. 13.** Assembly instruction for step 28. A28: finish the assembly of the gear body by installing the cover with two screws. Front and back pictures of the gear body on the final assembly.

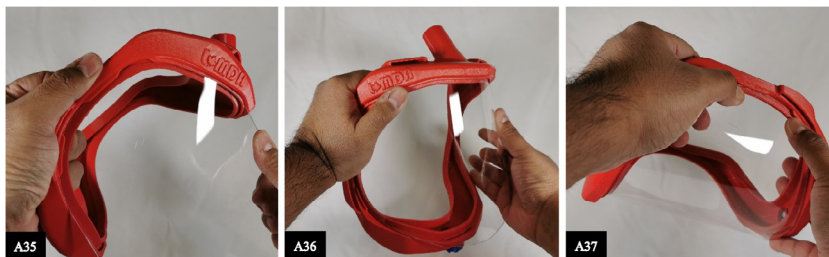
Confirm that the screen is well distributed along all the contour and while holding its position with one hand, insert the lock on the bottom of the mask, Figs. 17–A38. Next, take the neoprene strap and cut a piece with roughly the same length of the mask inside contour. It is better to leave some extra length to avoid any excessive waste. Then, starting from the middle



**Fig. 14.** Assembly instructions from steps 29 to 31. A29: tape the pattern on top of the clear screen, A19: mark the contour with a cutter, and A19: trim the contour with a heavy-duty scissor.



**Fig. 15.** Assembly instructions from steps 32 to 34. A32: take the film from the mask valve and place it on the exhaust cover, A34: locate the pins from the cover with the bottom of the mask, and A34: push the exhaust cover to fit with the bottom port.



**Fig. 16.** Assembly instructions from steps 35 to 37. A35: position one end of the clear screen on the mask, A36: insert the rest of the screen following the top flange, and A37: finish mounting the screen with the flanges on the other end of the mask.



**Fig. 17.** Assembly instructions from steps 38 to 40. A38: secure the screen in the mask with the front lock, A39: cut a piece of neoprene tape and put in on the contour of the mask, and A40: cut the remaining of the tape once both ends are together.

bottom, remove the adhesive from one end of the neoprene band, and paste it all along the edge of the mask, see [Figs. 17-A39](#). When you reach the starting point, take a cutter, and carefully remove the additional length, and leave a continuous band. It is recommended to make a diagonal cut to prevent any leakage, [Figs. 17-A40](#).

It is recommended to make a diagonal cut to prevent any leakage, and additional pressure might be necessary on different areas of the band while it sticks to the mask, [Figs. 18-A41](#). Take the flexible straps and pass them through the mask joints, [Figs. 18-A42](#). Form a cross with all the straps, as shown in [Figs. 18-A43](#). Depending on the straps, two of them might need to





**Fig. 18.** Assembly instructions from steps 41 to 43. A41: confirm the neoprene band has no gaps along all the contour of the mask, A42: pass the flexible straps on the mask joints, and A43: form a cross shape with them.

complete an entire line of the cross. Loose or adjust the strap according to your convenience. The mask should hold itself to the face without excessive force.

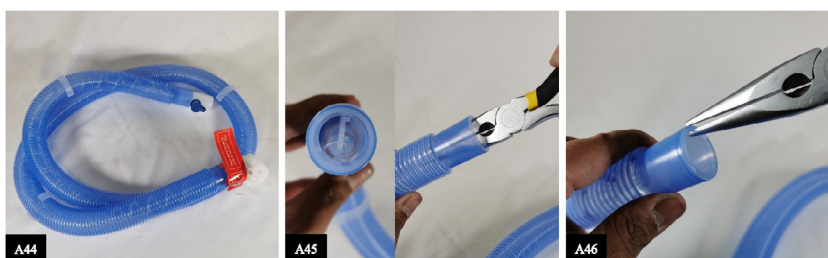
Take the most extended pipe from the CPAP package, [Figs. 19-A44](#), and remove any additional features not necessary for this respirator. These might include the plastic clips, plastic fitting, and internal electric resistance, as shown in [Figs. 19-A45](#). It is easier to remove the plastic fitting with a needle nose plier, but it is essential not to damage the blue ports, [Figs. 19-A46](#).

Once the blue hose is free from any additional feature, manually insert one end into the gear body, [Figs. 20-A47](#), and the opposite port should go on the respirator mask, [Figs. 20-A48](#). Use clockwise circular movements to ease the pipe's insertion and confirm that 2 cm of the pipe is covering each port, [Figs. 20-A49](#).

The personal respirator must be ready once all the steps are completed as per the previous instructions, and it should look like the one shown in [Fig. 21](#).

## Operation instructions

The next steps must be followed for the correct usage of the PAPR; see [Fig. 22](#). First, pass the end without the buckle of your belt through the gear body's support, as shown in [Fig. 22-\(S1 & S2\)](#). It is possible to use a dedicated belt for the respirator to wear it on top of your clothes or medical uniform; or, the same belt for your pants or jeans works perfectly. Then, connect the battery and turn on the respirator. Buckle your belt over your waist as you normally do with jeans, [Figs. 22-S3](#), and grab the mask with both of your hands, [Figs. 22-S4](#). Relieve the straps and wear the mask with a direction from top to bottom of your head, [Figs. 22-S5](#). This movement is easier if the straps hold with one hand while the other pull from the



**Fig. 19.** Assembly instructions from steps 44 to 46. A44: take the longest hose from the CPAP package, A45: remove any extra material with pliers, and A46: remove the fitting on the end of the hose.



**Fig. 20.** Assembly instructions from steps 47 to 49. A47: insert one end of the CPAP hose on the fitting of the gear body, A48: put the other end in the mask, and A49: confirm each end of the hose cover at least 2 cm of the fitting.



**Fig. 21.** Full assembly of powered and ergonomic personal respirator.

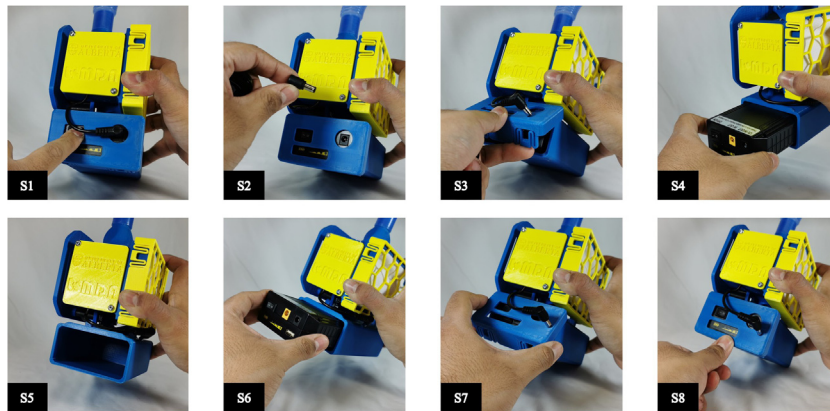


**Fig. 22.** Steps for correct wear of the respirator. S1: Pass the belt from the left end of the gear, S2: pass the belt thru the other end and balance the length to leave the device in the middle, S3: buckle the belt and turn on the battery, S4: grab the mask with both hand, one holding the straps and the other holding the bottom of the mask, S5: start wearing the mask by stretching the strap and pull from the back and top of your head towards the front and bottom, and S6: fit the mask to your best comfort.

bottom of the mask. Fit the mask to your best comfort, the pipe must rest in the middle of your head, and it is recommended to leave a single loop on the hose to avoid excessive agitation, [Figs. 22-S6](#).

The respirator can be removed by following the same steps explained above but backward. The only critical task to realize before removing the mask is to clean it with a disinfectant wipe before any procedure. This step's importance relates to the environment because even though the chamber inside of the mask is clean, the exterior could be contaminated with respiratory droplets.

To replace the battery, first, turn it off and disconnect the 12 V wire, [Fig. 23-\(S1 & S2\)](#). Then, simply pull the spring locks from the bottom of the holder, [Figs. 23-S3](#), and tilt the gear to extract the battery by gravity, [Figs. 23-S4](#). Clean the battery



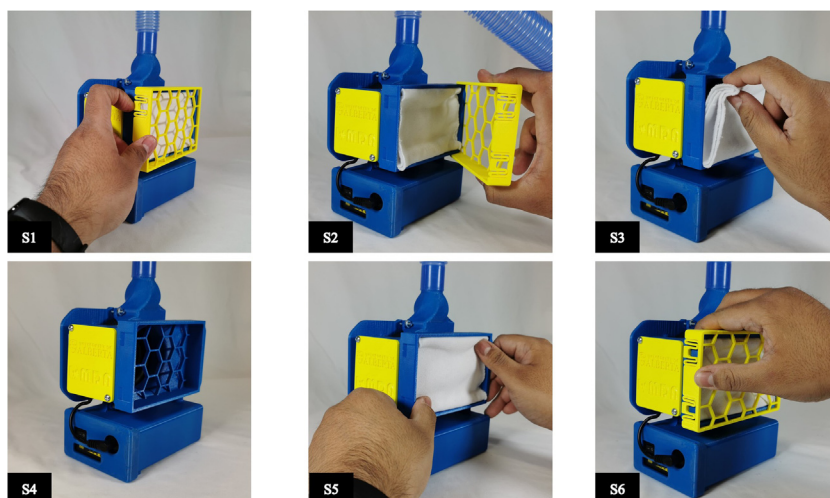
**Fig. 23.** Battery replacement steps. S1: turn off the battery, S2: disconnect the 12 V wire from the battery, S3: release the battery cover by pulling the lock springs and remove it completely, S4: tilt the device to extract the battery by gravity, S5: clean the battery holder in case any contamination exist, S6: put the new battery in the same orientation as the previous one, S7: mount the cover on the flange, and S8: push until the spring locks click and connect the 12 V wire.

holder in case it has any contaminant, Figs. 23-S5, and tilt the gear body to put the new battery in place, Figs. 23-S6. Mount the battery cover beginning from the top flange, Figs. 23-S7, and push until the spring locks click and the cover is flush with the battery, Fig. 23-S8. Notice that the battery has a specific orientation, and the cover should not allow another position.

The filter can be replaced or take it out to wash easily. To remove the filter cover, pull the spring locks from the sides, Figs. 24-S1, and grab the cover until it is released from the gear body, Figs. 24-S2, and leave it in a clean area. It is crucial to wipe the gear with disinfectant before this procedure to avoid any possible contamination. Take the filter with your fingers from one corner and pull until it is release, Figs. 24-S3. Consider this filter as contaminated and use proper precaution when taking it in your hands. Gloves could help as well as extensive hand washing. Clean the gear and cavity with disinfectant to prevent any contamination in the air circuit, Figs. 24-S4. Put the new or washed filter in the cavity while avoiding any air gab, Figs. 24-S5. Insert the filter cover levering from the right flange and push until the spring locks click and the filter is flush with the cover, Fig. 24-S6.

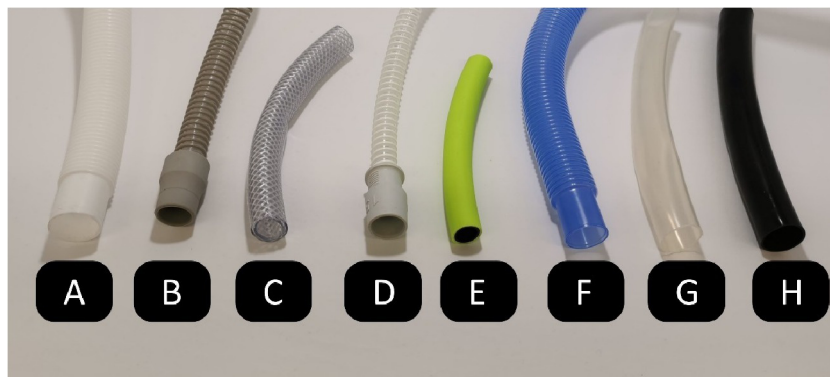
### Validation and characterization

The most important parameter for the respirator is the airflow with the full-face mask chamber's positive pressure. The NOISH specification requires a minimum of 4 Cubic feet per minute in a constant flow for this type of PAPR Thus, selecting an optimal pipe to connect the gear body with the mask was critical. For the selection of the optimal pipe, a quick analysis with



**Fig. 24.** Filter replacement steps. S1: pull the spring locks to release the filter cover, S2: pull until the cover is completely out of the gear, S3: take out the used filter with your fingers and clean your hands afterwards, S4: clean the cavity with disinfectant wipes, S5: push the new filter in the cavity avoiding any gaps, and S6: install the filter cover as shown on the assembly process.





**Fig. 25.** Hoses tested for optimal airflow. A) P.V.C. plumbing hose, B) gray 19 mm medical hose, C) clear plumbing hose, D) white 12 mm medical hose, E) green  $\frac{3}{4}$  inch general hose, F) blue 25 mm CPAP hose, G) clear 28 mm food grade hose, H) black 25 mm food grade hose. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**  
Airspeed results from the anemometer.

V (Volts)	A (Amps)	White PVC hose output (m/s)	Grey medical hose output (m/s)	Clear plumbing hose output (m/s)	White medical hose output (m/s)	Green hose output (m/s)	Blue hose output (m/s)	Clear hose output (m/s)	Black Hose output (m/s)
7.12	0.78	7.8	5.1	4.6	4.6	4.4	6.8	8.1	8
8.09	0.95	8.6	7	6	6.3	6.1	8.2	9.2	9.3
9.1	1.12	10.3	7.3	6.5	6.6	6.4	9.5	10.5	10.6
10.05	1.27	11.2	8.1	6.9	7.3	7.1	10.1	11.8	11.7
6.57	0.67	6.4	5.3	3.3	3.4	3.2	6.2	6.6	6.8
7.91	0.92	8.4	5.8	6.9	6.1	7.1	7.6	8.7	9

different hoses was implemented. The test was set with a gear body adapted to the hose diameter, a piece of hose with a minimum length of one meter, and the airspeed was measured with an anemometer (BTMETER BT-816B) at the input port of the mask. Then, the airflow was calculated knowing the port diameter of the mask. The variety of hoses used for the test can be seen in Fig. 22.

The variety of hoses used for the test can be seen in Fig. 25, and the results for the test can be seen in Table 1. Here not only was the airspeed measured, but the current consumption was taken into consideration to understand the time span for the battery. In this experiment, different hoses were tested to understand the impact on material, weight, and airflow, where more than half were achieving enough C.F.M.s. However, once the test was done, some issues appear with the pipes. For instance, the clear and black hose, Fig. 25 (G, H), was made from an incredibly soft material that any minimum bending would collapse the internal cavity. On the other hand, stiffer pipes, like the ones in Fig. 25 (A, C, E), could still collapse, and they were incredibly uncomfortable to wear. As the hose tried to keep its original shape, the mask on the user could go out of position, and the person wearing the PAPR would have to constantly accommodate the mask. Therefore, from all the pipes tested, only three had the potential for our respirator, the white and gray medical hose, and the blue CPAP hose.

Once the options were narrowed to only three, all measurements were taken into consideration. The three hoses could achieve the minimum airflow, but considering the shift length of 10 to 12 h from front-liners, the pipe with the least consumption will win. As the battery selected for the device has 8500 mAh, a current load of less than 700 mA will be required. This specification leaves the blue CPAP hose as the only option for our device. Notice that if the length of the shift is smaller, other hoses could be implemented.

## Discussion

### Function

The respirator has performed spectacularly in terms of airflow and ergonomics. The device is lightweight, and it is not as invasive as other brands in the market. However, there are areas of opportunity like noise and vibration. These were not formally tested for the current design but the stochastic usage of the device by the authors finds no serious discomfort. Still, a quick test with the smartphone app "Sound Meter" shows an increase of 17 dB when the device is activated. For this test, the sound was measured without the active device at 10 cm aside from the blower, showing a measurement around 30 dB; but

once the respirator is turned on, the result reach 47 dB. This indicates that the noise from the respirator is not excessive for normal working environments. The primary source of these concerns is the air blower but changing the component for a better-quality increases the cost dramatically. Thus, the respirator's redesign might be required to improve these features. Extra foam for the belt support could be included to disperse the vibration against the user. Adding some isolation like a double wall might be necessary. The current material for the mask's contour is neoprene, which is skin-safe for practically all users.

Nevertheless, the printed ABS's stiffness is not as comfortable as flexible silicon or TPU., like the cushion frame on snorkel masks. Including this feature will be ideal for the respirator. However, this kind of function is limited to 3D printing, requiring other technology like injection molding or casting, out of the project's scope.

### *Cost estimation*

Although the cost of the PAPR is currently one-third of the ones on the market, there is an excellent opportunity to reduce the cost of the device. First, the current cost for the 3D printing filaments is higher than off-the-shelve printers. This is because the printing machines require proprietary expendables, and the authors were limited in this area. Nevertheless, changing the kind of additive printer could drastically reduce the material cost; but it is vital to use a printer with a working area wider than 240 mm, which is the longest distance of the mask. It must have a double nozzle for dissolvable support. This kind of support is critical because of the acute angles in the mask and gear shape, which is impossible to remove manually. Another option for cost reduction is finding a replacement for the current CPAP hose. It is necessary to buy the entire CPAP set to acquire the pipe, and the rest of the parts are wasted. Then, by finding a hose replacement, the cost can easily be reduced. The only features to consider in the hose are having a minimum diameter of 25 mm and bending ribs to avoid collapse.

### *Future work*

The actual device was designed with a quick response in mind, and the physical prototype works as a proof-of-concept. However, as the device depends on 3D printing technology, the mass production of such equipment is held by design itself, as these parts are not compatible to be produced by injection molding process. One crucial step to achieve mass production will be to adapt the current design for injection molding or other mass-production technologies. There are several changes to consider when making this update; for instance, each part must have draft angles; the thickness of the walls must be constant and enough depending on the machines used; an injection flux must be set to design the molds, and the ejector pins must be located on a position hidden for the user. Another advantage for injection molding technology is the variety of material. This feature can make the respirator mask more ergonomic by implementing a soft rubber on the contour of the mask. This limitation constrains the current design for 3D printing and makes impossible to have a single mask for all faces.

Additionally, the device will require a NOISH certification for an appropriate mass production respirator while keeping in mind some of the available patents in a similar area [12]. Part of this certification requires testing the PAPR for the particles holding capacity as a whole, any possible leakage or perfect seal, its ergonomics, and all characteristics stated previously, like the battery capacity and the defogging feature.

## **Conclusions**

This article has just proven the feasibility of producing an open-source powered and ergonomic PAPR, which is designed for 12 h per time operation such as required by doctors, reconfigurable, easy to use, and maintained. This device takes advantage of 3D printing technology for the dedicated parts and quickly finds material for the rest. On top of that, the respirator is modular, and the replicator could change the design to fit their airflow, battery, and filter needs. The PAPR has an estimated working life of 12 h while achieving an airflow over 4.5 CFM, but the voltage could be adjusted for better. The user only must take into consideration the current increment and battery period reduction. With all shown in the article, it is expected that the proposed design meets or is close to meet all the requirements by NIOSH; although, further analysis is required to validate the airflow, leakage, and ergonomics accordingly. Once certification is completed with NIOSH and the CDC., the commercialization of this device could proceed.

## **Declaration of Competing Interest**

The authors state no financial affiliation external relationship to any third party. The usage of the filter from the company ACAMP Inc. (<https://www.acamp.ca/>) was only for the convenience and features of the device, but the respirator is not limited to this product; and, the author has no conflict with the audience if they desire to reproduce this respirator with an adaptation for their local filters.

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## Human and animal rights.

There were no trials nor analysis using human or animal subjects. Additionally, the articles' consent pictures belong to one of the authors, Emanuel Martinez Villanueva, who agrees on using these images.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ohx.2021.e00223>.

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