Powered Air-Purifying Respirator (PAPR)

Design Report

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Contents

1. About Us

Work on this project started in 2020 in Adelaide, South Australia in response to the COVID-19 crisis. Dr Shiranth Fernando, a registered dentist, had concerns that available personal protective equipment did not adequately protect health care workers. At the time, Nathan de Souza was studying Mechatronic Engineering at the University of South Australia. Shiranth approached Nathan and we formed a partnership to design and develop a suitable device.

We initially designed a head mounted face shield with cooling that prevented condensation of the visor. Soon we realised that our device should provide filtered air and full head protection which led us onto producing a powered air-purifying respirator (PAPR).

We also observed from the recent COVID-19 pandemic, that many industries were facing the challenge of protecting their employees from the viral airborne disease, forcing them to search for effective, affordable, and comfortable face shields to use in their workplace. Our research led us to believe that the current devices are too large, heavy, noisy, and expensive.

In 2021 we applied for and were awarded a development grant from the Medical Device Partnering Program (MDPP) sponsored by the South Australian Government. They offered us a $10,000 grant if we were able to find a manufacturer who could invest $5,000 into it. Unfortunately, we were unable to find an Australian company who had a commercial interest in our product.

In 2022, we decided to offer our device as an open-source medical device which has led us to Glia. We remain passionate about our device and the fact that it can provide a low cost, lightweight solution for those who require safe air respiration, facial protection, and cooling.

Figure 1: Development over 3 years

2. Introduction

Powered Air Purifying Respirators (PAPRs) have been around for many years. However, many are either too expensive to buy or too heavy to wear. In this report, we will first provide an overview of what is currently available on the market and identify the common issues associated with these devices. Then we will address how our device (this will now be referred to as the "Fernando & de Souza PAPR" – FDSPAPR) is different from the rest and how it solves some of the ongoing issues. Finally, we will go into detail about the extensive research and development we have undertaken to produce our current prototype.

3. Background

Healthcare workers (HCW) are vulnerable to contaminated airborne particles such as viruses or bacteria that may be inhaled when treating infectious patients. Personal protective equipment (PPE) such as masks, visors and respirators have varying levels of efficacy and vary significantly in cost.

Refer to Appendix A for info on the types of air-purifying respirators available.

This report focuses on the PAPR device which uses a powerful fan that sucks in the surrounding air, passes it through a filter and pumps it into a hood & face piece, known as the breathing zone. Since the air is pressurised, the user's exhaled air is passively removed from the breathing zone. The positive air pressure has a cooling effect on the face and reduces condensation on the visor. A PAPR with a loose-fitting hood & face piece does not require fit testing like a P2/N95 mask, making it convenient for users with facial hair. PAPRs also have a higher particle filtration rate than P2/N95 masks. Since the air inside is purified, a face mask is not necessary.

4. The Market

Several companies dominate the PAPR market including 3M, Stryker, Tecmen, Malina, Sundstrom and Honeywell. Most of these devices cost upwards of US$1,000.

Refer to Appendix B for a summary of the types of PAPRs available from different companies.

With reference to Appendix B and Figure 2, many of the devices contain a powerful fan and a large battery pack worn on a belt around the waist with a tube extending up from the fan unit into the hood & face piece. The belt unit usually has battery power indicators, fan control and filtration. With the many components required to be worn, these devices become heavy to wear and can be time consuming to put on and take off.

Figure 2: Example PAPR Indo PeRSo 3

Being able to hear your surroundings would be important in some industries. Therefore, having a hood which does not cover the ears would be suitable for certain environments. The noise level of the fan should not be too loud, otherwise audible warnings and important conversations would not be heard.

Studies indicate that PAPRs do not offer any additional protection during use compared to simpler and cheaper protection methods; however, the cooling effect and wearer comfort especially for long hours of continual use, mean they are popular with HCWs (Licina A, 2021).

5. Our Design

5.1 Current specifications

- Weight: 220g
- Dimensions: 170x240x210mm
- Noise Level: 65dBA
- Max Airflow: 300 litres/min
- Required Airflow: 170 litres/min
- Filtration: HEPA 13 Filter
- Power: 5V 2.1A
- Device running time with 10,000mAh Battery: 8hrs

Figure 3: Device Features

5.2 How it works

This device uses a small but powerful fan on top of the face shield to directly extract and filter surrounding air for the user to breathe in safely. This is a positive pressure, loose fitting respirator which therefore does not require an airtight seal. The user is able to adjust the fan speed to provide control of how much air is coming through for both ease of breathing and to control the amount of cooling experienced. The green power-on LED also changes in brightness based on the fan speed. If the power is disconnected for any reason, a bright flash from the red LED will be seen and the buzzer will sound indicating a loss of power.

5.3 How it is different

Our device is light weight at 220g as opposed to over 1Kg for most other PAPR devices. The power source is a USB power bank as opposed to a 12V large lithium battery array. The filter system is simpler, cheaper to make, and smaller since it is located on the top of the device rather than wearing a fan belt unit with a breathing tube at the back. It allows for control over the fan speed, so that the user can adjust it appropriately. The noise level of our device is significantly lower at 65dBA compared to others. The filtered exhaust outlet is often missing in similar devices, and this has led to HCWs having to wear a face mask in addition to the PAPR. Our device could also be a tenth of the cost of others at $100 AUD retail.

5.4 Regulatory considerations

Ideal PAPR specifications are based on a long list of standards depending on the country of manufacture and sale. Most of the standards are based on PAPRs used in industry for dealing with poisonous fumes and particulate matter like silica. In April 2020, the US National Institute for Occupational Safety and Health (NIOSH) decided to ease the requirements for health use due to an acute shortage during the pandemic. The new classification of PAPRs for non-industrial use is PAPR100-N and PAPR100-P. Type N is for use against non-oil-based aerosols and P for oil-based ones. Both are deemed to be more suitable for use by workers in the healthcare and public safety sectors.

Refer to Appendix C to see how the FDSPAPR device meets the current standards.

5.5 Intended end users

The end users of the FDSPAPR device are mainly healthcare workers and first responders. A simple version of this device will be available for workers and hobbyists interested in face protection and cooling. We intend to target the health care market globally as well as industrial workers needing enhanced environmental protection. The total value of this market in 2021 was over US$2.6 billion, with a predicted annual growth rate of 8.5% (Verified Market Research, 2023). We hope we can provide a better product that may disrupt the market due to its simple design, ease of use and cost.

5.6 Current plans

We currently have a working prototype. However, we will need to professionally test the airflow rate, safety mechanisms and indicators, the efficacy of the inhalation and exhalation filters and the permeability of the hood for this product to progress further. Once this has all been done, we hope to market the product to interested manufacturers and distributors.

Ultimately, we want to make this device available for people to easily access and hope to partner with a medical manufacturing company for future development and production. In the meantime, we have considered making this an open-source DIY product, allowing the public to make it themselves by providing them the 3D files, templates, and a list of the components, forming a community of interested makers who could help develop the product further. The instructions are available as an Instructables page which can be accessed via the link below.

https://www.instructables.com/DIY-Powered-Air-Purifying-Respirator-PAPR/

6. Research and Development

The initial goal was to design a head mounted face shield that prevented fogging of the visor and provide cooling to the face. We used an axial fan, internal batteries and a piece of surgical face mask for a filter. This worked very effectively during clinical trials however, many operators found the device too heavy and were concerned that contaminated aerosol could enter from the side of the face shield.

After several designs, we morphed the device into a small, lightweight, simple PAPR. We incorporated a more powerful centrifugal fan, a HEPA filter, complete isolation of the user via a hood, and supplied power via a small external power bank which can be kept in a pocket. We also experimented with LED lights to provide illumination for the operator but left this out of our final design due to the increased weight and no perceived benefit from the added illumination. We also incorporated a filtered outlet at the bottom of the face piece to allow exhaled air to leave the device without contaminating the surrounding area. The device was 3D designed and 3D printed using ABS material allowing us to test multiple prototypes.

6.1 Filtration

PAPRs require an excellent filtration system. One that is commonly used is a High Efficiency Particulate Absorbing (HEPA) filter. There are different levels of HEPA filtration; H12= 99.5%, H13= 99.95, H14= 99.995%. This compares favourably to P2/N95 face masks which only remove 95% of particles.

The FDSPAPR device uses 3 different types of filtration material. For the inlet vent, a prefilter is used followed by a H13 filter. The prefilter made of non-woven polypropylene material is used as an absorbing barrier to remove large particles before reaching the HEPA filter.

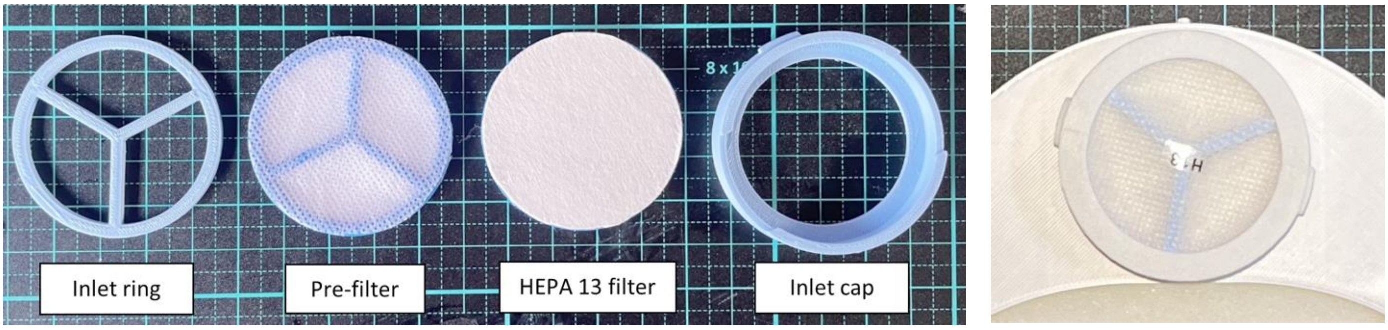

Figure 4: Inlet filtration components (left), components attached (right)

For the exhalation vent, a level 3 surgical face mask is used as the filter. During our research we found that most PAPRs used in healthcare do not have an exhalation vent or filter. Some surgeons wear surgical masks while wearing a PAPR. Although there is no evidence that devices without filtered exhalation vents cause contamination of a sterile surgical field, a filtered exhalation vent seems to be a sensible addition to any device used by HCWs (Howard RA, 2020).

Figure 5: Outlet filtration components (left), components attached (right)

Water droplet testing was conducted to verify the material's water resistance. As can be seen in Figure 6, we used water colour red paint for one droplet and tap water for the other droplet on each of the materials. Leaving it for 3 hours resulted in very little absorption in all three materials however, when wiping off the droplets with a tissue, the HEPA filter stained the most. We concluded from this that a prefilter was necessary before the HEPA13 filter to prevent large particles of debris clogging up the HEPA filter and enhances the water resistance of our inlet filter system. This is especially important when HCWs are involved in aerosol generating procedures such as dentistry.

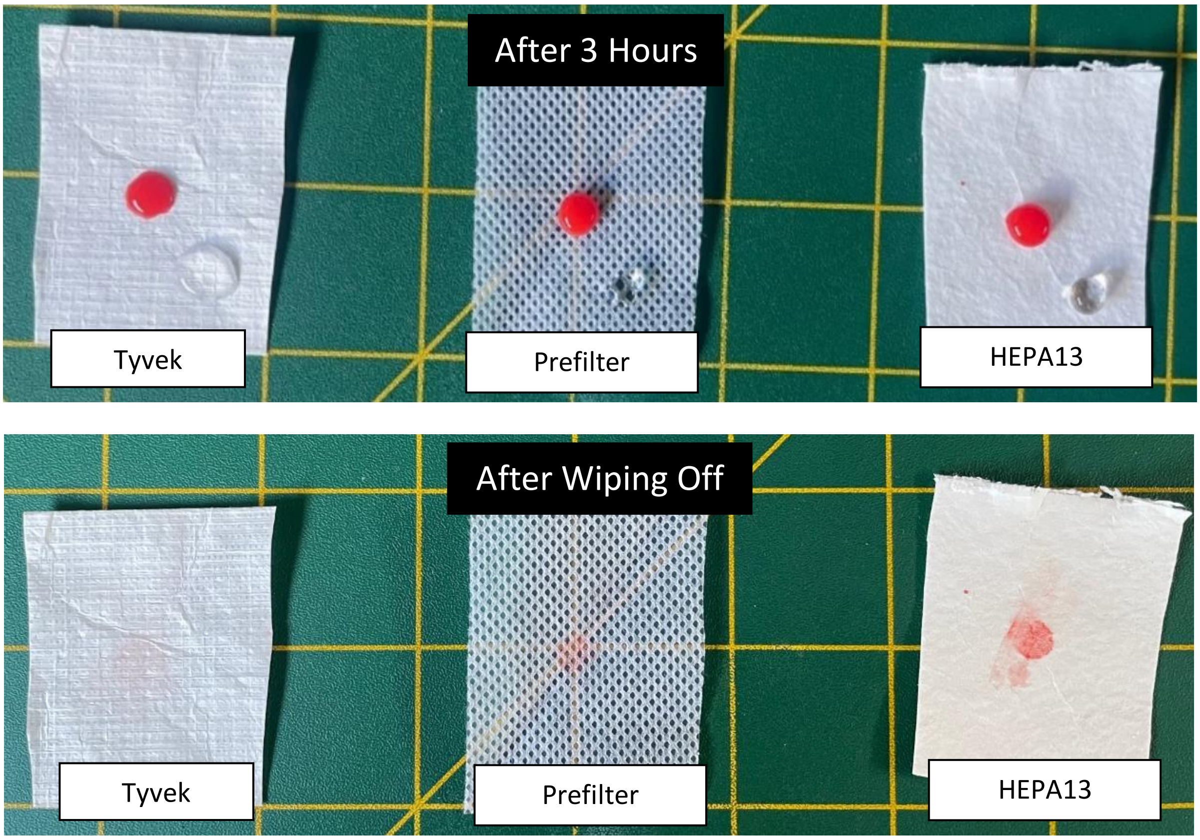

Figure 6: Water Resistance Testing

We also undertook fog testing to check whether the inlet filtration system is effective in removing particulate matter **(refer to Appendix D)**.

6.2 Fan Type and Airflow

Figure 7: Axial Fan

Since HEPA filters are thick, they reduce the air passing through them. As a result, we needed a fan which would generate enough pressure for air to flow through the filter as well as be small enough to fit into the housing.

We experimented with many different types of fans as well as different combinations and placements. We found that using an axial fan provided good coverage but low pressure and having two fans made it hard to fit other components even though the airflow was better.

Figure 8: Blower/Centrifugal Fan

After months of searching and experimenting, we finally found a fan which was powerful enough to provide adequate airflow. This was a 5V centrifugal blower fan which could be used at 9V (see Figure 8). We contacted the manufacturer asking about safety of the fan at higher voltages and was reassured that there was no problem since the fan was rated up to 10V.

Refer to Appendix E for the chosen blower fan specifications.

To ensure the safety of our device, each fan was tested by running at the highest speed at 9V for 48 hours non-stop.

The minimum airflow recommended for a loose fitting PAPR device is 170 Litres/min; our respirator provides a maximum of 300 Litres/min. We undertook many tests using two separate anemometers for measuring air velocity; this allowed us to calculate airflow in litres per min. We also used a laser tachometer to measure the fan speed in revolutions per minute. Heat build-up in the housing was monitored using a thermal imaging camera and an infrared thermometer.

Refer to Appendix F for how the airflow was measured.

6.3 Fan Control

We initially used a 100 Ω trimpot to vary the current flowing into the fan and hence its speed. This caused heat build-up in the trimpot and insignificant speed control. In addition, turning the trimpot involved the use of a screwdriver which was not ideal.

Figure 9: Trim pot

Instead, we found a better solution of using a Pulse Width Modulation (PWM) controller to change the fan speed which did not produce as much heat as the trimpot. As a bonus, the included potentiometer also acted as an on-off switch and the on-board LED varied in brightness as the pot rotated which we could use to our advantage.

Figure 10: PWM controller and pot-switch

6.4 Airflow Indicator

We wanted to provide a mechanism that allowed the user to monitor the airflow and provide a visual warning if there was a problem. After much research, we came up with a novel airflow indicator that utilises the Venturi effect and Bernoulli's Principle to provide a warning system. Basically, a clear plastic tube is placed in the user's field of view stemming from the base of the fan through the housing with a tiny foam ball in it. When there is adequate airflow, the ball will rise, otherwise the ball will stay down.

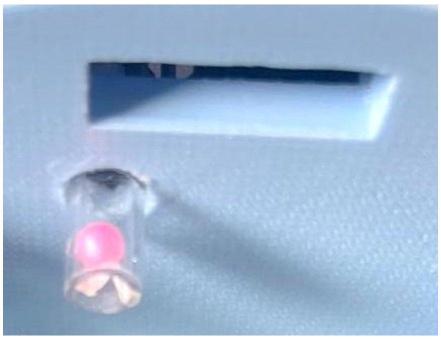

Figure 11: Airflow indicator

Refer to Appendix G on how the airflow indicator works.

This was left out of our instructables.com submission because of the need to open the fan and drill an access hole. For completeness and since it is a requirement for passing the relevant standard, we have added it here.

6.5 Power

Our device can be powered by any 5V 2.1A power bank with a USB A output connection port. This way it can be easily powered without having to be tied to a specific manufacturer. Some power banks have a push button start and some have an auto cut off feature if not in use after a period of time. This is important to keep in mind when turning off the potentiometer switch. If the power bank auto-cuts out, the device will not turn back on again. This can be easily fixed by simply unplugging and plugging back in the USB into the power bank.

Power banks can hold their charge for about 6 months, last 1-3 years, and can be recharged 500 to 1,000 times depending on the manufacturer. In normal use, power banks may get a little warm but should not get hot. If overheating occurs, stop charging or discharging until the temperature drops back down to the room temperature.

Power banks contain an integral circuit to ensure they always produce a constant output voltage. This makes it hard to measure the battery capacity externally. To circumvent this problem, we recommend the use of a power bank with a digital battery indicator display (preferably a numerical percentage) to show the remaining battery capacity. It would be sensible to change the power bank when the capacity reaches 5%. Since our device requires only a small amount of energy to power the components, a 10,000 mAh battery will last for 8 hours of continual use at the highest fan setting. It can comfortably fit inside a pocket without being too heavy or hot.

6.6 Power off warning system

The warning circuit inside the respirator detects complete power loss instantaneously via a flash of red light and a three second audible buzzer alarm. Since the device is loose fitting, the user will still be able to breathe comfortably inside the hood if the power cuts out, but should reasonably quickly replace the power bank with a new one as it can get a bit stuffy inside after a while.

We have recently been looking at implementing a backup battery system inside the housing. If there is a loss of power, the alarm system will activate, and the backup battery will immediately provide energy to the fan for 15 minutes. To ensure the user is aware that the device is running on backup power, an orange colour LED will be visible and stay on until the reserve power is depleted. This is still in a testing phase but hopefully will be integrated into our next version of the PAPR.

6.7 Component Layout

Due to limited space in the housing, we had to make sure that everything in the housing could fit nicely inside as well as decide what should and should not be included. The definite components we needed were the blower fan with the PWM controller and the pot switch. The rest of the components would be extras to ensure that the device meets certain standards as well as certain people might want specific features over other features due to the many applications this device can be used for.

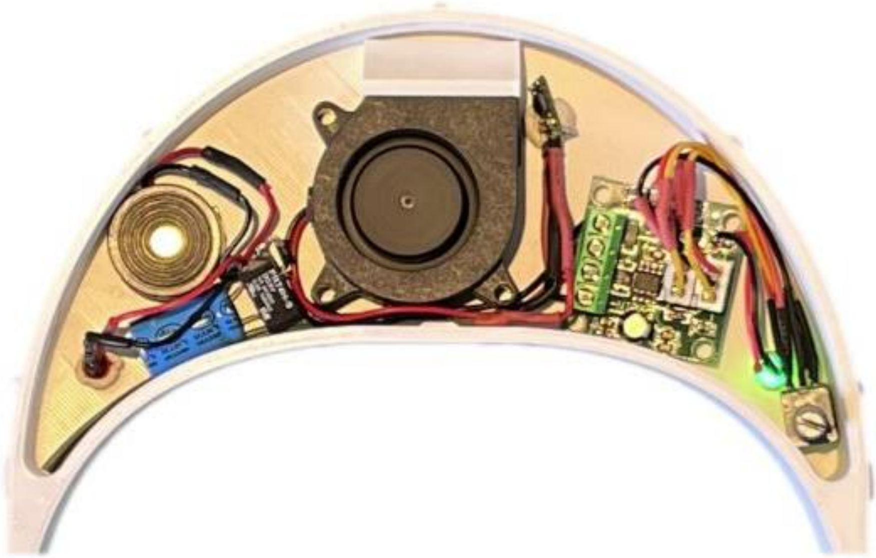

Figure 12: Component Layout

We wanted the circuitry to be as simple as possible so that anyone could make it themselves and even manipulate it to their liking without having to start from scratch. The below circuit diagram directly corresponds with the layout of the components for ease of component placement, wiring and testing in the housing.

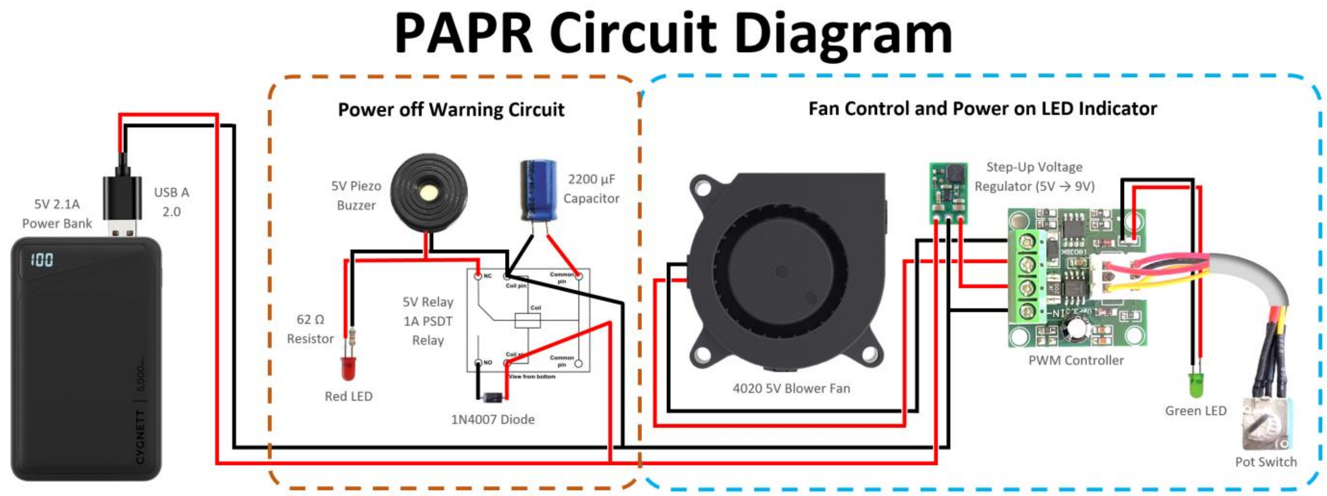

Figure 13: Circuit Diagram

6.8 The Visor and Hood

The visor and hood are an important part of the protection system. We used a commercially available face shield made of Polyethylene Terephthalate Glycol (PETG); this provides good protection and transparency without visual distortion, as long as the operator remembers to remove the cellophane protection sheets on both sides.

Figure 14: Visor (left), visor attached to hood (right)

We found using double sided sticky tape and polyester thread for sewing, secured the visor to the hood nicely. It is worth remembering that although we need a good seal around the device, the visor and the hood do not need to be airtight since this is a loose fitting PAPR.

We used a hood design which goes around the ear because it allows for use of stethoscopes and facilitates communication.

The hood is made of a material called Tyvek which is a resilient, water resistant, breathable and tear resistant material making it ideal for use as a hood for a PAPR. Most PAPR manufacturers who make breathable hoods use Tyvek.

The device prevents contaminated air from entering the breathing chamber by the positive air pressure it produces. The face shield and hood prevent aerosol and large liquid and solid splashes from coming into contact with the wearer.

The hood was designed to be easily detached from the housing and be easily decontaminated for reuse. The visor is held in position securely by posts that project from the housing.

6.9 Head Strap

We experimented with many systems to secure the device to the user’s head. We started off with a cheap headband which had adjustable knobs to tighten the top and back supports. However, thinking long term, we thought it best to try to develop our own head strap design. We investigated multiple configurations from cutting plastic card to go around the head and adding velcro for tightening. This did feel slightly sharp around the edges and was hard to keep the velcro connection in place. Finally, we decided that a simple elasticated strap was most effective providing the best comfort with minimal effort to make.

Figure 15: Cheap headband (left), plastic cut card (middle), elastic strap (right)

6.10 Noise Level

PAPRs will be noisy compared to face masks and non-powered respirators. One of the standards for PAPRs is the ability of the HCW and patient to be able to communicate without shouting. A maximum noise level of 80 dBA is stipulated (see Figure 16 for comparison chart). Our device noise level is under 65 dBA; we used a sound level meter to confirm this value.

Decibel Level Comparison Chart

Environmental Noise	*dBA*
Jet engine at 100’	140
Pain Begins	*125*
Pneumatic chipper at ear	120
Chain saw at 3’	110
Power mower	107
Subway train at 200’	95
Walkman on 5/10	94
Level at which sustained exposure may result in hearing loss	*80-90*
City Traffic	85
Telephone dial tone	80
Chamber music, in a small auditorium	75-85
Vacuum cleaner	75
Normal conversation	60-70
Business Office	60-65
Household refrigerator	55
Suburban area at night	40
Whisper	25
Quiet natural area with no wind	20
Threshold of hearing	0

Figure 16: Decibel Level Comparison Chart

6.11 Weight

The FDSPAPR device weighs approximately 220g and is comfortable to wear on the head for long periods. Most other devices weigh at least 1 kg with the heavier parts worn on a belt around the waist. We did consider including batteries and adding external lighting however, we found these specific components contributed significantly to the overall weight and therefore left them out of the final design.

6.12 Costs

The cost to make this device was $125.73 AUD ($85.53 USD). However, some parts were purchased in bulk. Therefore, based on the amount of material which was actually used, the cost can be reduced to $41.38 AUD ($28.12 USD). Most of the materials for construction of our PAPR can be sourced from AliExpress www.aliexpress.com. The fan is specific to this device and can be purchased from https://yunfanpower.com/dc-blower-fan/64.html. The Polulo voltage regulator can be purchased from https://www.pololu.com/category/136/voltage-regulators. If both these items are replaced, please ensure that you thoroughly test your device to ensure that it is safe and provides adequate airflow.

Refer to Appendix H for overall cost table.

6.13 Maintenance

Disinfection is the process of eliminating or reducing harmful microorganisms from inanimate objects and surfaces. Sterilisation is the process of killing all microorganism including spores. PAPR devices can be disinfected after use but cannot be easily sterilised. We have designed the device so that it can be easily cleaned and disinfected. The external surfaces can be decontaminated with hospital grade disinfectants and reused while the filters should be replaced each time after use.

Our PAPR can be reused as there are electronic components inside which you would not want to throw away. However, we do recommend that the face shield is cleaned with a mild disinfectant and the HEPA filters inside the inlet and outlet valves be replaced regularly. The specifics for when to replace and disinfect would depend on the activity being undertaken.

Refer to Appendix I for our recommended decontamination procedure.

7. Future Development

We have designed, developed, and tested this device for over three years. It is our intention, with help from Glia, to undertake further testing to validate the results we obtained. Some of the testing for PAPR 100-N devices need to be undertaken in specialised laboratories. Despite the relaxing of some of the specifications with PAPR 100 ruling by NIOSH, it will involve commitment and finance to get the device approved. Some of these tests are described in this article: https://www.federalregister.gov/documents/2020/04/14/2020-07804/approval-tests-and-standards-for-air-purifying-particulate-respirators#print

Refer to Appendix J to see what testing equipment we used.

We are currently working on a DIY/Hobbyist head mounted face shield with cooling which we expect to have mass market appeal. This device will have the 5V blower fan running at 9V. There will be no hood and the outlet air vent will be adapted so that the air is directed toward the user's face rather than straight down. There is no need for a power loss warning circuit since it would be obvious to the user if it occurred. An adjustable 5W LED loupe light will also be added to this device.

Figure 17: Prototype with Loupe light

We have discussed a version of this device that would be simple to construct and provide good protection. It would be more suited for HCW in developing nations, especially tropical climates where cooling of the face would be welcome. The most important parts of the device are the fan with speed controller, filters, hood and visor. The power loss warning system and airflow warning indicators provide reassurance but are not essential. Since this device is head worn any loss of power and/or airflow would be obvious to the user.

The current version of the FDSPAPR device is also being improved. We are hoping to incorporate a short acting backup battery if the power bank fails. Also, coming up with a solution which does not require the use of a sewing machine is something we are considering.

8. Bibliography

Centers for Disease Control and Prevention (CDC). (2019, September). *What Are Air-Purifying Respirators?* Retrieved from The National Personal Protective Technology Laboratory (NPPTL): https://www.cdc.gov/niosh/npptl/pdfs/FY17_N95infographicWhatAreAPR-508.pdf

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Appendix A – What are Air-Purifying Respirators?

What are Air-Purifying Respirators?

Air-purifying respirators (APRs) work by removing gases, vapors, aerosols (droplets and solid particles), or a combination of contaminants from the air through the use of filters, cartridges, or canisters. These respirators do not supply oxygen and therefore cannot be used in an atmosphere that is oxygen-deficient or immediately dangerous to life or health. The appropriate respirator for a particular situation will depend on the environmental contaminant(s).

Filtering Facepiece Respirator (FFR)

- Disposable
- Covers the nose and mouth
- Filters out particles such as dust, mist, and fumes
- Select from N, R, P series and 95, 99, 100 efficiency level
- Does NOT provide protection against gases and vapors
- Fit testing required

Elastomeric Half Facepiece Respirator

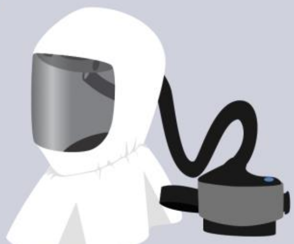
- Reusable facepiece and replaceable cartridges or filters
- Can be used to protect against gases, vapors, or particles, if equipped with the appropriate cartridge or filter
- Covers the nose and mouth
- Fit testing required

Elastomeric Full Facepiece Respirator

- Reusable facepiece and replaceable canisters, cartridges, or filters
- Can be used to protect against gases, vapors, or particles, if equipped with the appropriate cartridge, canister, or filter
- Provides eye protection
- More effective face seal than FFRs or elastomeric half-facepiece respirators
- Fit testing required

Powered Air-Purifying Respirator (PAPR)

- Reusable components and replaceable filters or cartridges
- Can be used to protect against gases, vapors, or particles, if equipped with the appropriate cartridge, canister, or filter
- Battery-powered with blower that pulls air through attached filters or cartridges
- Provides eye protection
- Low breathing resistance
- Loose-fitting PAPR does NOT require fit testing and can be used with facial hair
- Tight-fitting PAPR requires fit testing



CDC NIOSH
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

https://www.cdc.gov/niosh/npptl/pdfs/FY17_N95infographicWhatAreAPR-508.pdf

Appendix B – Current PAPRs Available

3M Versaflo Easy Clean PAPR Kit | 3M Versaflo Heavy Industry PAPR Kit | 3M Versaflo PAPR Painters Kit | 3M Versaflo Healthcare PAPR Kit | 3M Full Face Reusable Respirator 7800 | Ford 3M PAPR

Indo PeRSo 1 | Indo PeRSo 3 | Stryker Flyte | Stryker T7 | CleanSpace ULTRA | GMI FELIX100 PAPR

Tecmen TM-H1 | Tecmen TM-H2 | Drager X-plore 800 | Gentex Pureflo ESM+ PAPR | Gentex Pureflo PureLite Xstream PAPR | FlexAir PAPR

JSP PowerCap Active | JS PowerCap Infinity | MaxAir | Malina CleanAir Pro | Malina Infinity 1 | Malina Infinity 2 | Malina Infinity 3

Sundstrom SR520 supplied-air hood | Sundstrom SR530 supplied-air hood | Sundstrom SR580 supplied-air helmet & visor | Sundstrom SR562 supplied-air shield | Sundstrom SR200 full face respirator | Sundstrom SR540ex intrinsically safe supplied-air shield

Honeywell Turbo Visor PAPR | Honeywell North 7600 | Honeywell North Survivair | Allegro Supplied Air shield | Allegro EX Pro Shield | Allegro Full Mask Respirator

BioVYZR | Bubble PAPR | WIN HealthLabs PAPR | National University of Singapore | Maxisafe Air Hood Face Shield

Appendix C – FDSPAPR Standards Check

Available Standards:

- UK standards: http://www.cn-csas.com/media/20200424105933YR.pdf
- US standards: https://www.cdc.gov/niosh/npptl/respstandards/papr.html

How does the FDSPAPR device meet these standards?

- **Minimum airflow rate of 170 litres per minute for loose-fitting PAPRs** – Our PAPR provides a maximum of 300 litres per min.
- **No fit test –** Our PAPR has a loose fit hood.
- **Maximum 80 dBA noise level** - Our PAPR is below 65 dBA.
- **Light weight** - Our PAPR weighs 220g; most PAPRs are over 1kg.
- **Low cost** - Our PAPR could retail at under $100; most PAPR devices cost over $1,000.
- **Can be used in a sterile field** - Our PAPR has a filtered exhalation valve using a Level 3 surgical mask.
- **Effective protection from particles** - Our PAPR uses a HEPA 13 filter.
- **Not too big –** Our PAPR is smaller and less bulky than traditional PAPRs
- **Reduce condensation of visor –** the airflow is strong enough to quickly defog the visor
- **Cooling air –** Our PAPR circulates the air inside the hood creating a cooling sensation. The air intake can only be as cold as the surrounding air temperature.
- **Can be worn with spectacles and medical magnification loupes** – Our PAPR provides a large enough gap between the face and visor for face wearables.
- **Communication not compromised** - With our PAPR, the operator and patient can see and hear each other.
- **Interchangeable batteries** - Our PAPR can be powered by any 5V 2.1A power bank with a USB socket.
- **Batteries must last minimum of 4 hours when fully charged -** Our PAPR can run for 8 hours with a 10,000mAh power bank.
- **Device battery capacity feedback** - Not possible for device supplied by a power bank.
- **Device airflow feedback** - Our PAPR has an airflow reduction indicator.
- **Visible and audible alarms** – Our PAPR has this for power cut or depletion.
- **Australia TGA Class 1 non-sterile, non-measuring medical device** - To be actioned.
- **Minimal Maintenance** - Our PAPR can be reused however, we do recommend that the face shield is cleaned with a mild disinfectant and the filters inside the inlet and outlet valves be replaced regularly.
- **Can be safely used short term with fans not working** – Our PAPR's loose-fit hood and exhalation vent will allow breathing for a short time without fan assistance
- **Adjustable fit** – Our PAPR has toggles used to tighten the hood and the headband elastic can be cut to a desired size.

Appendix D – FDSPAPR Fog Testing

To investigate whether the inlet filtration system is effective in removing particulate matter, we used a fog machine and an air quality monitor device. The air quality monitor device can measure the particulate matter (PM) of 1, 2.5 and 10 microns in size. 2.5 microns is equivalent to 1/20th of the size of a human hair. Particulates of PM 2.5 come from wood stoves, car emissions, and industrial manufacturing. Examples of the latter are sulphates, nitrates, organic compounds, and trace elements.

Fog Machine

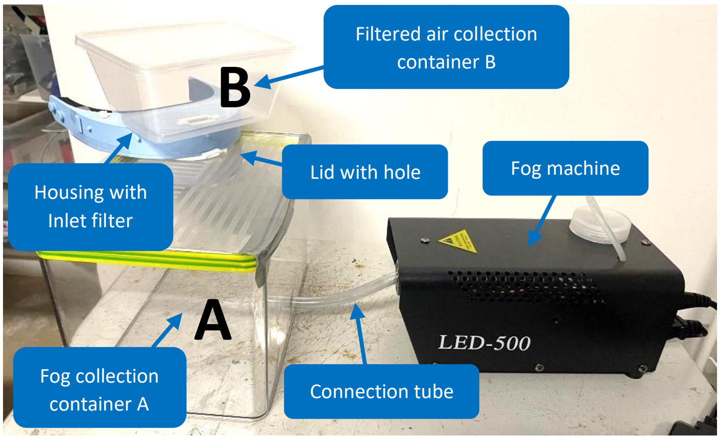
Air Quality Monitor Device

About the air quality monitor device

- We used an Autens air quality monitor to record several indicators of pollutants. https://autensdirect.com/product/air-quality-monitor-indoor-air-quality-pollution-detector-accurate-tester-for-hcho-formaldehyde-tvoc-pm2-5-pm1-0-pm10-with-temperature-humidity-monitoring/
- These machines have reasonable accuracy after calibration; recordings using the same machine in different environments are comparable.

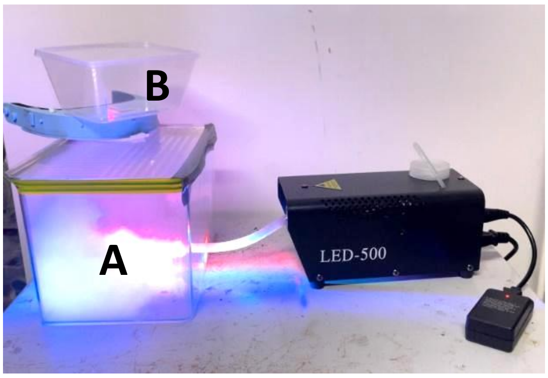
Setup

The fog machine is connected into a fog collection container A via a tube. Then a hole is made in the lid of the container for the housing to sit on top of with the inlet filter attached. Finally, a smaller collection container B is placed on top of the outlet of the housing where the filtered air passes through. This container has a perforated lid to prevent pressure build up.

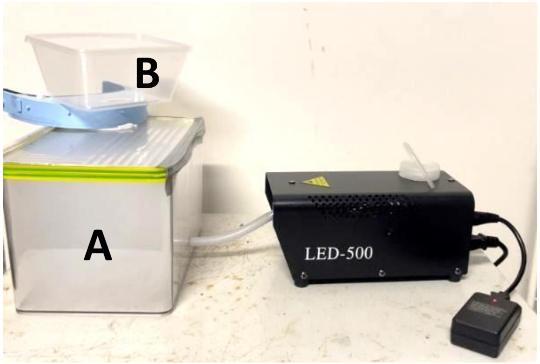


Test Setup

Method



1. The air quality monitor device was used to record the PM before, during and after the fogging/filtration occurs.
2. The fog machine is primed and started. It momentarily pumps a mixture of glycol, air, and water vapour into the collection container A; it becomes opaque due to the dense fog. The machines LED light array is momentarily triggered.
3. The connection tube is closed using a clamp.



4. This mixture is then sucked up by the respirator filtration system inlet and pushed out from the outlet as filtered air into the smaller container B.
5. After a few minutes, the fog collection box A becomes transparent as all the vapour has been extracted.

Results

Table: Particulate Matter Measurements

Container	Testing Stage	PM 1	PM 2.5	PM 10
A	Before Fog/Filtration	001	002	002
	During Fog/Filtration	300	395	458
	After Fog/Filtration	002	003	003
B	Before Fog/Filtration	001	003	003
	During Fog/Filtration	001	003	003
	After Fog/Filtration	001	003	003

Observations

No fog is seen exiting the respirator outlet; this is an indication that the filtration system is working. The results above also indicate that the filtration system is working effectively in removing particulate matter of size PM 1, 2.5 and 10.

HEPA 13 filters can theoretically remove at least 99.97% of dust, pollen, mould, bacteria, and any airborne particles with a size exceeding 0.3 microns (µm).

Appendix E - FDSPAPR Chosen Blower Fan

40*40*20*mm 12v dc brushless waterproof high pressure centrifugal blower fan for industrial

Brand:Yun-Fan YUNFAN POWER CO.,LIMITED
Model: DC Blower Fan 4020
Size: 40*40*20*mm
Voltage:5V/12V/24V
Speed: 3800-6500 (R/min)
Weight: 22 (g)
Bearing type:Ball & Sleeve
Life time:Ball type 50000 hours,Sleeve type 30000 hours

Website: https://yunfanpower.com/dc-blower-fan/64.html

- To get the combination of air flow and low noise, this fan was found to be reliable, safe and low cost.
- Two wire
- Waterproof, high pressure
- Bought from Yun-Fan for US $2.20 each
- Contact Manager Mr Black Tan: black@yunfanpower.com
- The manufacturer has tested and confirmed that it is safe to use the 5V model at 9V

Appendix F - FDSPAPR Measurement of Airflow and Air Velocity

A lot of time and effort has gone into research, development and rigorous testing of this device. The efficacy of the fan is of particular importance. Although the blower fan is rated for 5V, it has a control input range of 0-10V, so running it at 9V is not a problem. It was tested by the manufacturer, and we ran every fan at full power and 9V for a minimum of 48 hours continuously.

What is an anemometer?

An anemometer is a device used for measuring wind speed and direction. It measures air velocity and not air pressure. Two handheld anemometers A and B were used to test the air velocity of expelled air from the centrifugal respirator fan.

A = NDi KC-280A Anemometer https://www.ebay.com.au/p/20021411392

B = E916DT-A, https://www.entosupplies.com.au/equipment/field/field-supplies/hand-held-anemometer/

Airflow Calculation

Airflow is the volume of air moved by a fan per unit of time, usually expressed in cubic feet per minute (cfm) or meters cubed per second (m^3/s). Airflow can be recorded in Litres per min (L/min).

We used this website for our calculations: http://www.calculatoredge.com/optical%20engg/air%20flow.htm

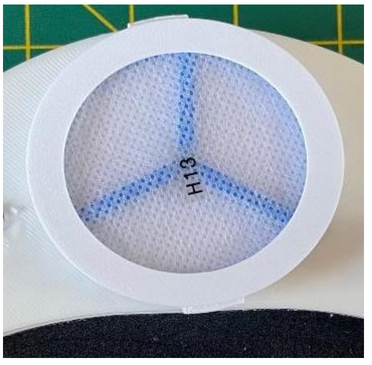
Airflow Test 1 – Workbench straight out fan

We tested the fan on the workbench. The size of the fan duct is 15mm x 25mm. Device A gave a reading for velocity of 10.3 m/s and device B 10.7 m/s. This gave an approximate airflow rate of 3.9 L/s which is (3.9 x60) 234 Litres/min. This is well above the minimum airflow rate necessary for loose fitting PAPRs= 170 L/min.

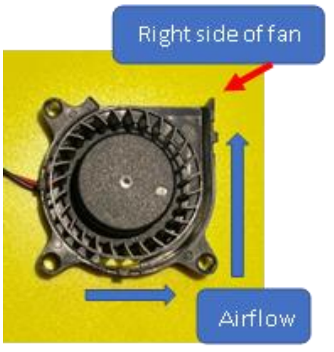
Airflow Test 2 – From housing outlet with inlet filter

We then recorded the airflow from a working respirator complete with the inlet filter. Device A recorded 22 m/s and device B recorded 26 m/s. The size of the outlet duct is 10mm x 25mm approximately. Taking the lower figure of 22 m/s, we obtained a calculation of 5.5 L/s which gave a final figure of 330 Litre s/min.





Why is there an increase in airflow from bench test to finished prototype? Airflow is very difficult to measure in small fans. We noticed that when measuring the (user's) left side of the respirator vent, we obtained a lower reading than the right side. This can be explained by the centrifugal fan blade design which forces the air to come out faster on the right side. We took several readings from the centre and used a lower-than-average reading of 22 m/s for our calculation. The increase in airflow is due to the decrease in the size of the outlet.



Bernoulli's Principle: This mathematical principle states that if the air is flowing through a tube and the tube's diameter decreases, then the velocity of the air increases, the pressure decreases, and the flow remains constant so long as the air density is constant.

Air Velocity Fan Speed Test

Yun Fan 4020 blower fan 5V, model FB4020B(S)05H (high pressure) is recommended for use in this PAPR. If you are unable to get hold of one of these, ensure you purchase 5V 40x40x20mm high pressure blower fan. Check the outlet of the fan is 15mm x 25mm.

Test your fan is at 5V 2.1A (power bank is ideal) and measure the air velocity using the anemometer (preferably one similar to the ones we used) and the fan spin speed using a laser tachometer.

We used the UNI-T model UT373. It is easy to use and costs under $30 from Ebay.

Website: https://meters.uni-trend.com/product/ut373/

Procedure with 5V supply

1. Cut a tiny piece of reflective tape (supplied) and remove the protection tape on both sides.
2. Stick it to the fan's rotation body ensuring the shiny end is facing you.
3. Start the device and focus the red dot onto your tape and move it a tiny bit until a signal received symbol flashes or is permanently displayed; it looks like a wifi symbol lying on its side. This means the laser has reflected back to the tachometer and ready.
4. Start the fan and take the reading in RPM. The fan speed should be about 6,500 RPM.

9V supply test

After this has been tested with 5V, connect the fan to the housing circuitry which contains the voltage regulator boosting the input voltage to 9V. The fan speed should be about 9,000 RPM and air velocity about 10 m/s.

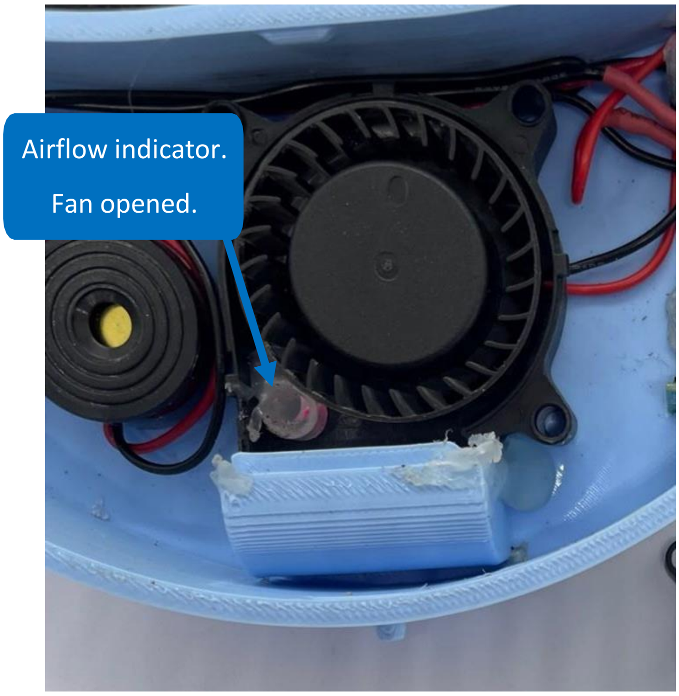
Appendix G - FDSPAPR Integral Airflow Indicator

This simple indicator is an extra safety measure to show that there is adequate airflow. The noise from the working fan and the green power on indicator light do not guarantee that there is adequate airflow. For example, the fan could be rotating slowly or there may be a blockage in the fan.

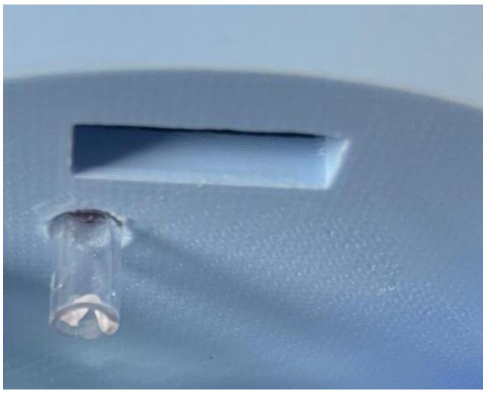
The indicator relies on Bernoulli's Principle and the Venturi effect to produce a weak vacuum. When the air is flowing freely out of the fan, the vacuum pulls the tiny pink polystyrene ball into the housing.

If power is cut or the airflow from the fan is compromised, the vacuum stops, and the pink ball descends and is visible.

The indicator is small and transparent and placed high up, so it does not interfere with the user's vision.



Poor airflow (ball has not risen)



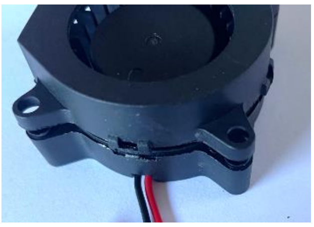
Good airflow (ball has risen)

How to make the airflow indicator

Materials required:

- Transparent plastic tube - 6mm outer diameter, 3mm inner diameter, 15mm length
- Small 6mm drill
- Hot glue gun
- Screwdriver
- 3mm foam ball
- Highlighter

Procedure:



1. Open the blower fan using a thin flat end screwdriver; be careful not to break the retaining clips keeping the halves of the fan housing together.

2. Locate the 6mm diameter dent mark on the base and drill a hole through it.

3. Cut a plastic tube with an external diameter of 6mm and internal diameter of 3mm at 15mm length.
4. Place the fan base onto the housing where it is connected to the funnel and mark the area of the 6mm hole onto the housing.
5. Drill through the housing where the hole was marked.
6. Use a highlighter pen to colour the polystyrene ball and ensure that it freely moves in the plastic tubing.

7. Place a thin strand of hot glue across one end of plastic tube still allowing air to flow through.
8. Secure the fan onto housing and thread the closed end of plastic tube through the housing and fan base and ensure that 10mm is sticking out of housing.
9. Seal the open end of the tube with another thin strand of hot glue.

10. Use more hot glue to secure the plastic pipe to the fan base being careful not to spill the glue onto the fan blades.
11. Close the fan lid and test. When the fan is working, the ball will rise to the top of the tube. When the fan stops, it will fall and be visible.

Appendix H - FDSPAPR Materials Cost

* Note exchange rate used for 11th May 2023: $1.00 AUD = $0.68 USD

Part Name	Amount Supplied	Amount Used	Supplier Cost (AUD)	Supplier Cost (USD)	Usage Cost (AUD)	Usage Cost (USD)	Supplier Link
Electronic Components							
Cabling							
1 - Heat Shrink 2mm Diameter Red and Black	5 metres	1 metre	$0.76	$0.52	$0.15	$0.10	https://www.aliexpress.com/item/1005002450682083.html
2 - USB 2.0 Type A Plug 4-pin Male Connector	5 pcs	1 pc	$1.08	$0.73	$0.22	$0.15	https://www.aliexpress.com/item/1005004940845387.html
3 - 1m Grey/Black Figure 8 Cable 28 AWG	1 metre	1 metre	$0.35	$0.24	$0.25	$0.17	https://www.aliexpress.com/item/1005005332693644.html
4 - Stranded Wire: Black, 28 AWG	50 metres	0.3 metres	$16.88	$11.48	$0.10	$0.07	https://www.aliexpress.com/item/1005005450546335.html
5 - Stranded Wire: Red, 28 AWG	50 metres	0.3 metres	$16.88	$11.48	$0.10	$0.07	https://www.aliexpress.com/item/1005005450546335.html
Fan control circuit							
6 - 4020 Blower Fan 5V model FB4020B(S)05H	1 pc	1 pc	$2.20	$1.50	$2.20	$1.50	https://yunfanpower.com/dc-blower-fan/64.html
7 - PWM DC Motor Speed Controller with Pot Switch 1803B	1 pc	1 pc	$1.68	$1.14	$1.68	$1.14	https://www.aliexpress.com/item/1005002205934989.html
8 - 9V Step-Up Voltage Regulator U3V16F9	1 pc	1 pc	$11.60	$7.89	$11.60	$7.89	https://core-electronics.com.au/9v-step-up-voltage-regulator-u3v16f9.html
9 - 5mm 3V Green LED	100 pcs	1 pc	$0.59	$0.40	$0.01	$0.00	https://www.aliexpress.com/item/1005005182451381.html
Power-off warning circuit							
10 - 16V 2200uf Electrolytic Capacitor	5 pcs	1 pc	$1.30	$0.88	$0.26	$0.18	https://www.aliexpress.com/item/4000031065489.html
11 - 1A 5VDC SPDT PCB Mount Mini Relay	10 pcs	1 pc	$1.11	$0.76	$0.11	$0.08	https://www.aliexpress.com/item/32963196636.html
12 - 1N4007 1000V 1A Silicon Diode	100 pcs	1 pc	$0.73	$0.50	$0.01	$0.00	https://www.aliexpress.com/item/1005002772647658.html
13 - 62-ohm Resistor	100 pcs	1 pc	$0.55	$0.37	$0.01	$0.00	https://www.aliexpress.com/item/1005005310500584.html
14 - 1.5-24V Piezo Chassis Mount (active) Buzzer	1 pc	1 pc	$0.67	$0.46	$0.67	$0.46	https://www.aliexpress.com/item/4001221164950.html
15 - 5mm 3V Red LED	100 pcs	1 pc	$0.59	$0.40	$0.01	$0.00	https://www.aliexpress.com/item/1005005182451381.html
Power source							
16 - 5V 10000mAh USB A Power Bank	1 pc	1 pc	$13.56	$9.22	$13.56	$9.22	https://www.aliexpress.com/item/1005001590958124.html
Materials							
Elastic							
17 - White Braided Elastic 20mm x 5m	5 metres	0.8 metres	$0.58	$0.39	$0.09	$0.06	https://www.aliexpress.com/item/32835986498.html
18 - White Braided Elastic 6mm x 5m	5 metres	1.5 metre	$1.17	$0.80	$0.35	$0.24	https://www.aliexpress.com/item/1005004641843380.html
Tape/Glue/Solder							
19 - Hot Glue Gun Sticks 7mm x 100mm	30 pcs	1 pc	$4.60	$3.13	$0.15	$0.10	https://www.aliexpress.com/item/33012695191.html
20 - Sticky Tape 18mm x 12m	12 metres	1.5 metres	$0.43	$0.29	$0.05	$0.04	https://www.aliexpress.com/item/4000161688372.html
21 - Double-Sided Tape White 3mm x 8m	8 metres	0.5 metres	$1.39	$0.95	$0.09	$0.06	https://www.aliexpress.com/item/1005003258328064.html
22 - Transparent Super Glue	12 pcs	1 pc	$1.75	$1.19	$0.15	$0.10	https://www.aliexpress.com/item/1005004377879839.html
23 - Non-Toxic Glue Stick	12 pcs	1 pc	$7.58	$5.16	$0.63	$0.43	https://www.aliexpress.com/item/1005001721527939.html
24 - 1mm Solder	100 g	10 g	$7.12	$4.84	$0.71	$0.48	https://www.aliexpress.com/item/1005005004488963.html
Sheets/Filters							
25 - H13 HEPA Filter	100 kg	0.1 kg	$6.50	$4.42	$0.01	$0.00	https://www.alibaba.com/product-detail/Factory-Direct-Supply-HEPA-Glass-Fiber_1600806152835.html
26 - Du Pont Tyvek 1443r Fabric	50x100 cm	50x80 cm	$7.61	$5.18	$6.09	$4.14	https://www.aliexpress.com/item/1005002715429366.html
27 - Non-woven Polypropylene Material	100x18 cm	10x10 cm	$1.12	$0.76	$0.06	$0.04	https://www.aliexpress.com/item/1005003942344949.html
28 - Level 3 Surgical Face Mask	10 pcs	1 pc	$3.49	$2.37	$0.35	$0.24	https://www.aliexpress.com/item/1005001835669245.html
29 - Face Shield Visor and Lightweight Foam	1 pc	1 pc	$0.90	$0.61	$0.90	$0.61	https://www.aliexpress.com/item/4000919187977.html
Other							
30 - Safety Pin	100 pcs	1 pc	$2.25	$1.53	$0.02	$0.02	https://www.aliexpress.com/item/1005004828520921.html
31 - Stopper Cord Lock Bean Toggle Clip	12 pcs	2 pcs	$1.51	$1.03	$0.25	$0.17	https://www.aliexpress.com/item/32703750628.html
32 - White Sewing Thread 500m	900 metres	3 metres	$2.11	$1.44	$0.01	$0.00	https://www.aliexpress.com/item/1005004885280621.html
33 - 1kg ABS or PETG Filament 1.75mm	1 kg	0.1 kg	$5.09	$3.46	$0.51	$0.35	https://www.aliexpress.com/item/1005001937526579.html
		Total:	**$125.73**	**$85.53**	**$41.35**	**$28.12**	

Appendix I - FDSPAPR Decontamination Procedure

This protocol is based on the CDC guidelines for PAPRs (link below).

https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/powered-air-purifying-respirators-strategy.html

Definitions

- Cleaning: the physical removal of dirt, dust and contaminated materials from a surface.
- Disinfection: the process of eliminating or reducing harmful micro-organisms from inanimate objects and surfaces.
- Sterilisation: the process of killing all micro-organism including spores.
- Neutrawash 0.5%: a mild detergent cleaning product.
- Super SaniCloth wipes: a disinfectant cleaning product.
- PAPR devices can be disinfected after use but not easily sterilised.

We have designed the device so that it can be easily cleaned and disinfected. The filters should be replaced regularly, and the external surfaces can be decontaminated with hospital grade detergents & disinfectants.

Procedure

1. Wear appropriate PPE.
2. Disassemble the PAPR device into the following parts:
   a. Housing with lid attached
   b. Ventilation inlet filter cap & ring with filters attached
   c. Hood and visor
   d. Ventilation outlet base, cap and filter
   e. Power bank
3. Remake the inlet ring with a new HEPA filter and pre-filter.
4. Replace the outlet filter.
5. Remove the double-sided sticky tape that attaches the lid to the hood.
6. Inspect the parts for damage.
7. Clean the remaining parts with a disposable cloth dipped in warm water (43 degrees C, 120 degrees F) and Neutrawash solution. Wipe each part several times.
8. Wipe these parts again with another cloth dampened with warm water to remove the detergent.
9. Disinfect the parts by wiping with a Sanicloth ensuring at least one minute contact time of the solution with the component. Wipe each part several times.
10. Use one or more cloths dipped in clean warm water to remove the disinfectant.
11. Leave to dry and reinspect before reassembling.
12. Please note the cloths used for cleaning and disinfecting must not be dripping with liquid, since there is a danger of moisture reaching the electrical components inside the housing and power bank.
13. It may be difficult to decontaminate the sponge forehead cushion on the housing, depending on the material being used.
14. Visors that are covered in solid particles of debris from aerosols generating procedures can be easily scratched when they are decontaminated. Running the visor under water before processing is recommended.
15. If Neutrawash is not available, any mild detergent can be used.
16. If Super Sanicloth wipes are not available, household bleach 5% with a 1:24 bleach to water ratio and 5 minutes contact time could be used.

Appendix J - FDSPAPR Testing Equipment

A: Nice Power R-SPS3010 variable power supply
B: UNI-T UTi260B thermal imager
C: Jaycar mini fog machine
D :Autens air quality monitor
E: UNI-T UT373 mini tachometer
F: Micron Q1266 sound level meter
G: Ndi KC-280A anemometer
H: Etekcity infrared thermometer
I: UNI-T digital lux meter
J: Micron Q11334A multimeter
K: Homegeek micro digital weighing scale
L: UNI-T USB tester
M: LED tester
N: E916DT-A anemometer
O: Ozito digital humidity and temperature meter