REDUCING EXPOSURE TO AIRBORNE VIRUSES USING AIR FILTRATION SYSTEMS

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AirLabs, Copenhagen, 25 March 2020
Updated 9 April 2020

Summary
The world is struggling to confront the COVID-19 pandemic caused by the highly contagious severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), first identified in late 2019 in Wuhan China [1]. There is a concerted effort to reduce transmission so that the health care system is not overwhelmed. Viruses mainly leave an infected person's body in connection with air and are introduced into a new host by inhalation or contact, for example by touching a contaminated surface and then your eye or nose. The dose of the virus which uninfected people receive matters both in terms of reducing transmission and because dose is linked to the severity of the illness.

There is a particular need to protect front line workers, who are regularly put into situations where exposure to the virus could potentially be high. The implementation of defensible ventilation systems for provisional and improvised health care facilities can form one part of this protection. For products which filter aerosol particles from contaminated air, the key factor is the rate at which clean air can be produced by the air filtration system. This is particularly important for spaces that are continuously being contaminated by respiration. The goal in this context is to have high throughput in order to quickly reduce viral load. We argue that air cleaning in enclosed spaces is an effective tool to combat transmission via airborne particles.

Virus transmission
Coronaviruses including SARS-CoV-2 can be spread by airborne transmission [2]. Viruses are emitted by infected persons via respiratory droplets produced during coughing, sneezing, talking and breathing. Larger droplets will quickly fall out of the air while smaller droplets may persist as aerosols. People become infected when virions (viruses outside of a cell) enter the body via the respiratory system, eyes, nose, and mouth, with onset of symptoms in 2 to 14 days. Recommended measures for prevention of transmission include washing hands, maintaining distance and not touching the face; at present there is no vaccine or antiviral treatment [3]. This paper will focus on *airborne transmission,* a mechanism which does not involve physical contact in any way.

Our understanding of airborne transmission is evolving rapidly. Professor Lydia Bourouiba of MIT studies the transmission of pathogens using fluid dynamics and epidemiology. Her paper in the Journal of the American Medical Association (26 March 2020 [4]) addresses the issue of aerosol versus droplet transmission, which is based on an outdated model of disease transmission. She writes that *'..current understanding of the routes of host-to-host* *transmission in respiratory infectious diseases are predicated on a model of disease transmission developed in the 1930s that, by modern standards, seems overly simplified. Implementing public health recommendations based on these older models may limit the effectiveness of the proposed interventions....The dichotomy of large vs small droplets remains at the core of the classification systems of routes of respiratory disease transmission adopted by the World Health Organization and other agencies, such as the Centers for Disease Control and Prevention. These classification systems employ various arbitrary droplet diameter cutoffs, from 5 to 10 µm, to categorize host-to-host transmission as droplets or aerosol routes. Such dichotomies continue to underly current risk management, major recommendations, and allocation of resources for response management associated with infection control, including for COVID-19.'* The conclusion, supported by measurement of the lifetime of the virus in wet aerosol particles of several hours [5], is that aerosol transmission is a viable pathway and a very real concern.

Dr. Harvey Fineberg, Chair of the Standing Committee on Emerging Infectious Diseases and 21st Century Health Threats wrote in a summary, *'Currently available research supports the possibility that SARS-CoV-2 could be spread via bioaerosols generated directly by patients' exhalation...While the current SARS-CoV-2 specific research is limited, the results of available studies are consistent with aerosolization of virus from normal breathing.'*

The study by Liu et al. [6] examined airborne transmission in a hospital in Wuhan, China during the outbreak. In this study, *'Thirty-five aerosol samples of three different types (total suspended particle, size segregated and deposition aerosol) were collected in Patient Areas (PAA) and Medical Staff Areas (MSA) of Renmin Hospital of Wuhan University (Renmin) and Wuchang Fangcang Field Hospital (Fangcang), and Public Areas (PUA) in Wuhan, China during COVID-19 outbreak. A robust droplet digital polymerase chain reaction (ddPCR) method was employed to quantitate the viral SARS-CoV-2 RNA genome and determine aerosol RNA concentration.' The authors of the paper conclude, 'Room ventilation, open space, proper use and disinfection of toilet can effectively limit aerosol transmission of SARS-CoV-2. Gathering of crowds with asymptomatic carriers is a potential source of airborne SARS-CoV-2. The virus aerosol deposition on protective apparel or floor surface and their subsequent resuspension is a potential transmission pathway and effective sanitization is critical in minimizing aerosol transmission of SARS-CoV-2.'*

There is clearly a link between dose and transmission [7]. In addition, a recent article by Drs Rabinowitz and Bartman in the New York Times illustrates the link between dose and the severity of illness [8]: *'Virus experts know that viral dose affects illness severity. In the lab, mice receiving a low dose of virus clear it and recover, while the same virus at a higher dose kills them. Dose sensitivity has been observed for every common acute viral infection that has been studied in lab animals, including coronaviruses.'*

These findings indicate that the transmission of SARS-CoV-2 via bioaerosols within an enclosed space is a clear possibility, for many hours after a host has left. Therefore, effective filtration of the air in enclosed spaces will reduce the risk of virus transmission. The most commonly used techniques for filtering the air are particle filters and electrostatic precipitators (ESPs).

Function of a particle filter

A particle filter is, on the face of it, a relatively simple technology. It is comprised of a dense layer of fibrous material which stops particles from passing through it. However, the mechanics of how it traps particles is not entirely intuitive, as it happens on a very small scale where the physics that apply are not something we experience in everyday life. All that is required for a microscopic particle to be trapped by a filter is for it to collide with one of the filter fibres. The filter does not act like a "net", only catching particles above a certain size, but can actually trap particles much smaller than the "holes" in the filter.

Impaction and interception

Of the mechanisms which can trap a particle in a filter, it is impaction and interception which are most easily relatable. These mechanisms apply to larger particles, which in this context means particles around 1 µm in diameter or larger. As one of these particles moves through the air and into a filter its trajectory will cause it to collide with one of the fibres of the filter material. This happens as it is not able to follow the airstream around the fibre without colliding, due to its size or momentum. These mechanisms are shown in figure 1.

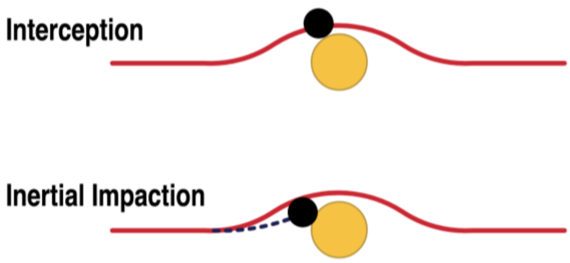

Figure 1. The red lines indicate air moving around a filter fibre (yellow circle). The black dots indicate particles. [9]

Diffusion

When considering particles significantly smaller than 1 µm in diameter there are other factors to take into account, arising from the smaller size. These particles are so small that they are carried along with an airstream, so potentially carried around the fibres of the filter. However, on this scale the particles are affected by collisions with the gas molecules which make up the air. This causes movement, which is no longer in a straight line, but instead has a large element of "randomness", an effect called diffusion. This means that rather than following the stream of air through the filter, they move more randomly, and eventually this causes a collision with a filter fibre. This mechanism is shown in figure 2.

Figure 2. The red line indicates air moving around a filter fibre (yellow circle). The black dot indicates a particle. [9]

Due to this diffusion mechanism, there is no lower limit to the size of particles which can be removed by the kind of filter.

Filter grades
Particle filters are graded based on their efficiency, to allow for the selection of the appropriate filter for a specific task. Filters of a higher grade remove a higher percentage of particles from the air passing through them, but they also have higher density, and this presents a greater restriction to the airflow. This restriction to airflow is important, as the fan which is driving the air through the filter must overcome this resistance. Therefore, if the fan is kept constant, an increase in the filter grade means that while the filtered air may be fractionally cleaner, much less of it is produced. This demonstrates that the selection of a filter of the highest grade may not be sensible, and in fact the grade must be chosen which allows for both high particle removal AND high air flow.

An example of the particle removal efficiency of two filters is shown below in figure 3, a HEPA filter and a slightly coarser “F9” filter. It is clear that for these filters the removal efficiency is extremely high, over 95% for the full range of particle sizes. The “F9” filter will however allow for a higher throughput of air, as it is less dense than the HEPA filter.

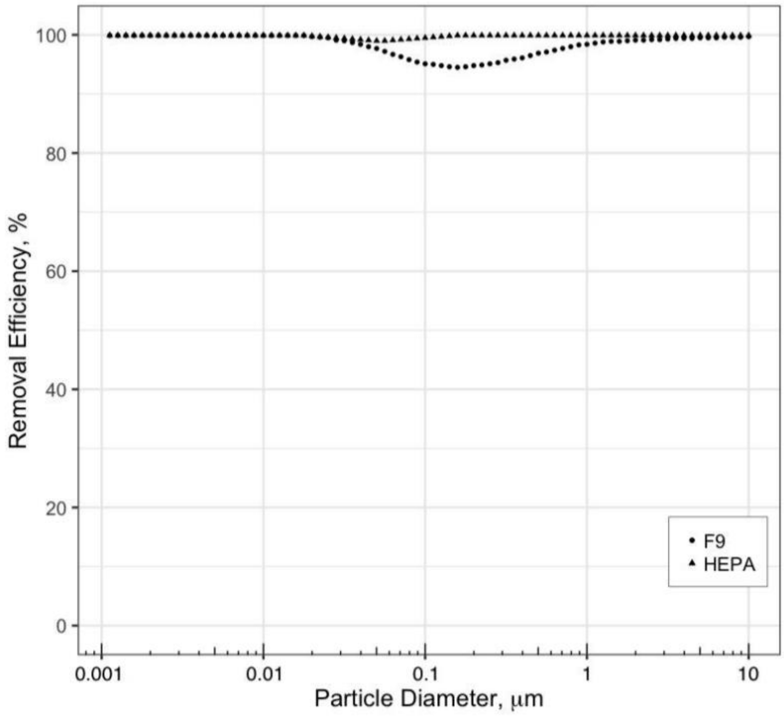

Figure 3. Single pass particle removal efficiency of a two particle filters, a HEPA filter and an F9 grade filter (according to EN779) [10]

The particle size at which these filters show the lowest removal efficiency is at approximately 0.2 µm, the point at which the combined effect of the diffusion and impaction mechanisms is lowest.

Function of an ESP

The basic principle of an electrostatic precipitator (ESP) is to ionise particles passing through it, after which they are strongly attracted to a series of plates upon which they are trapped. A typical ESP is constructed with a row of thin wires which is followed by a stack of metal plates through which air can flow. A negative voltage of several thousand volts between the wires and the plates leads to the particles becoming charged as they pass through the wires, they are then attracted to and trapped by the plates as they pass through them.

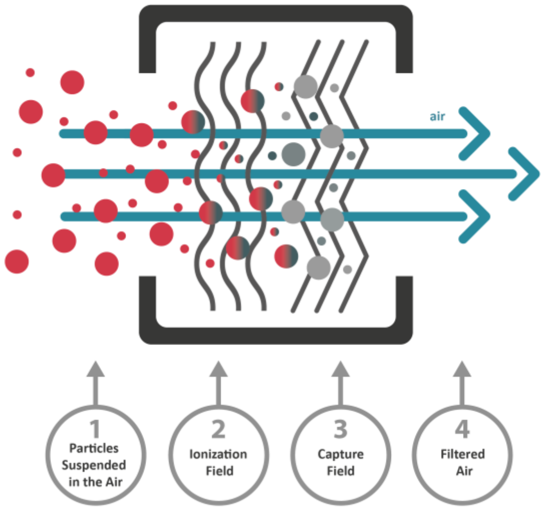

Figure 4. Schematic of the function of an Electrostatic Precipitator.

The efficiency of ESP devices can be extremely high, they can reach the same level as the most efficient fibre-based particle filters, while at the same time creating very little flow resistance. They perform especially well on particles at the smaller end of the range, and therefore ESP technology is an excellent choice for removal of particles less than 5 µm in diameter. Figure 5 shows data for removal of particles by an ESP over a large range of particle sizes. This shows that even under high volumes of air flow the efficiency of removal of all particle sizes remains extremely high.

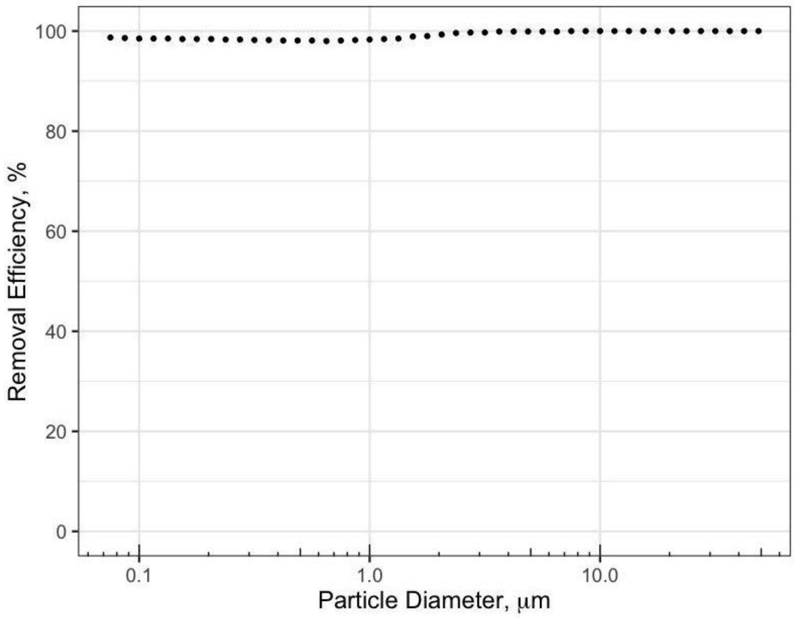

Figure 5. Removal efficiency of an ESP over a particle range from 0.07 µm to 14 µm *[11]*

The Coronavirus virion has a spherical structure with a diameter of 0.05 µm - 0.2 µm [12]. A particle of this size is efficiently trapped by both of the filtration methods that have been described here.

As a side-effect of the high voltages used, small amounts of ozone can be produced in an ESP. This must be removed from the airstream before it passes back into a room, and a specific gas filter must be used which can perform this function.

Reducing virus transmission using air filtration

It has been clearly demonstrated over the previous two sections that:

1. One of the modes of transmission of SARS-CoV-2 is via bioaerosol.
2. Air filtration technology of the appropriate type is capable of removing bioaerosol.

There is therefore a clear mechanism for air filtration devices to reduce the amount of virus suspended in the air. By using an air filtration device in an enclosed space and reducing the airborne virus load there is potential for reducing the probability of transmission of SARS-CoV-2. This includes the following scenarios [13]:

1. Rooms with infected patients
2. Hospital Environments (and shared closed spaces generally)
3. Closed vehicles

1. Rooms with infected patients

A patient infected with SARS-CoV-2 will constantly release particles containing the virus into the room they are in. In a hospital room this will lead to a gradual increase in the viral load in the air, as well as on surfaces as the particles settle. Using an air filtration device here to reduce the loading could be of great benefit to health workers or others who are required to enter the room. Lower levels of virus in the air means fewer are taken into the airways of health workers upon respiration, and less settling on their clothes and skin, reducing the possibility for transmission.

There may also be a benefit here for the infected patient. As virus-laden particles are consistently released by the patient there is a clear possibility for them to be re-inhaled from the surrounding air. Although the patient is already infected, this may be a route by which the virus spreads to other parts of the lungs [13].

2. Hospital environments (and shared closed spaces generally)

In a hospital environment there are areas visited by many people, of whom some will be infected, either showing symptoms or asymptomatically. The use of large-scale air filtration will lower the levels of airborne virus in these spaces and is therefore a key element in any strategy to reduce transmission and especially to protect vulnerable persons

3. Closed vehicles

There are two clear potential uses for an in-vehicle air filtration device.

1. To clean the air within an enclosed space during the time between occupation by two different people, for example cleaning the air inside a taxi between customers.
2. To reduce the levels of airborne SARS-CoV-2 within a vehicle cabin while it is occupied.

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Clean Air Delivery Rate

In all of these scenarios there is a crucial factor which determines how much of the airborne virus load will be removed - the Clean Air Delivery Rate (CADR) of the air filtration device. This is defined as the number of cubic meters of 100% clean air produced per hour (m^3/hr). The CADR is a result of both the particle removal technique used in the device and the throughput of the fans used. The higher the CADR is, the more air will be cleaned in the room and the lower the virus levels will be. Standard calculations show that if the CADR is high enough to clean the air in a room or vehicle ten times per hour, then this can lead to a more than 90% reduction of particles in under 14 minutes [14].

Air pollution and viral transmission

Polluted air is known to affect the entire body including the heart and lungs [15] and is responsible for at least eight million premature deaths every year [16]. Several lines of evidence show that viral infections including coronavirus are exacerbated by underlying health issues including the health damage from air pollution. There is evidence and significant concern that COVID-19 will have a more serious impact on people who are exposed to air pollution. Studies of previous coronavirus family outbreaks have shown greater mortality for those exposed to toxic fumes. Studies of the SARS coronavirus outbreak in China in 2003 found that living in a polluted area lead to twice the mortality of those living in a less-polluted area [17]. A study by Ciencewicki and Jaspers presents convincing evidence that the incidence of viral infection is linked to the concentration of atmospheric particulate matter [18]. Several mechanisms may be at work. First, it is well known that air pollution reduces the health of the lung and the entire person, making them less able to fight infections [19]. Second, the studies described below show that exposure to air pollution leads to increases in viral infection. Third, as described below, atmospheric particulate matter acts as a carrier for the transport of biological contaminants including viruses. In addition to being a carrier, atmospheric particulate matter is a substrate that allows viruses to remain active much longer than would otherwise be the case.

Korean research demonstrated a link between fine dust in the air and the incidences of acute respiratory tract infections caused by the respiratory syncytial virus (RSV), adenovirus (HAdV), rhinovirus (HRV), human metapneumovirus (HMPV), human coronavirus (HCoV), human bocavirus (HBoV), human parainfluenza virus (HPIV), and influenza virus (IFV) [20]. Research has demonstrated correlation between avian flu and airborne dust [21]. The spread of syncytial virus (RSV) in children is correlated with the concentrations of PM10 and PM2.5 [22]. The number of cases of measles in 21 Chinese cities in 2013-14 was correlated with PM2.5 [23]. The spread of measles virus in Lanzhou China was linked to levels of atmospheric PM [24]. In Italy, the rate of spreading of COVID-19 was greater in areas with high PM pollution (e.g. Po Valley), as compared to other regions including areas with high or higher population density (Rome) [25]. Based on this evidence, atmospheric particulate matter is an effective vector for the transport, spread and proliferation of viral infections.

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Conclusions

The air filtration methods described in this paper are capable of efficiently removing particles from the air which could otherwise transmit viruses to new hosts. Using these methods to produce an adequate CADR in relation to the size and occupation rate of a room or space, an air filtration device can ensure that the exposure of individuals in that room to airborne SARS-CoV-2 will be significantly lower. Clearly, this has the potential for reducing the ease of transmission of the virus.

There are many situations in which there is potential for implementation of air filtration with this aim, and where they are not currently being used. In all of the use scenarios described in this article air filtration offers people an extra layer of protection from SARS-CoV-2.

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