

# Are Our Buildings Making Us Sick?

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## Participants

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The following discussion concerns the power of HEPA filtration and other devices used in healthcare, corporate, education and residential sectors when managing clean air quality. The history and background of indoor air quality and strategies used to improve indoor air will also be on topic.



# Are Our Buildings Making Us Sick?

Doctor Jeffrey Siegel and Doctor Elliott Gall



Doctor Jeffrey Siegel



Doctor Elliott Gall

## IAQ – A brief history

The main question in relation to air quality is: Are our buildings making us sick? Most likely indoor air quality has had some impacts on our performance and productivity, and definitely the lack of proper air management has increased viral transmission. Looking as far back as the Bible, there is a plenty of evidence to that indoor air quality was acknowledged as a health issue. An excerpt from Leviticus offers instructions on how to mitigate a moisture problem in the home and ironically now, instead of engaging a priest to solve the problem, we contract a mould remediator. Even two hundred years ago more formal studies of indoor air quality had already begun. German chemist Max von Pettenkofer was concerned with indoor air quality and gave advice on how to improve it. At that time Harriet Beecher Stowe, who was a prominent abolitionist in the US and who wrote extensively about life in the domestic realm, included whole chapters in her books about indoor air quality, and the importance of proper ventilation. The fundamental message is that the level of indoor air quality can affect a variety of health outcomes, both acute and chronic. There was also consideration given to how that quality existed in a building and affected individuals in decision making, productivity, general well-being and health.

## Causes of Poor Indoor Air

Around the world and at certain times of the year and day, poor quality outdoor air is a reality. In many cases poor ventilation and the fact people spend about 90% of time inside buildings, leads to a variety of exposures and health effects. This has always been a long-term reality and the question is how it can be solved. The primary solution is to ventilate enclosed spaces properly and apply supplementary sources when fresh ventilation isn't possible.

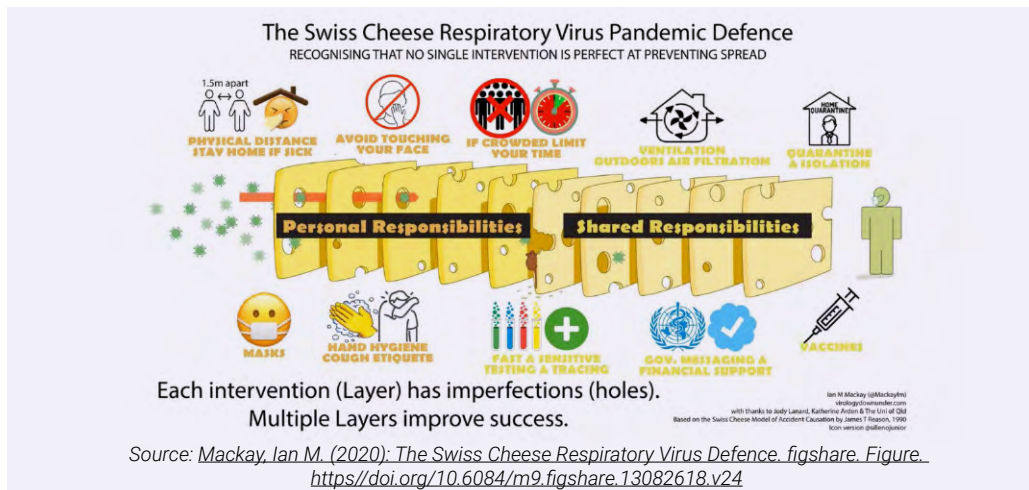
The advent of COVID-19 has presented several challenges in that domain. Conversely it has offered an opportunity to actually start thinking about and improving indoor air quality. There is a layer model that applies to all respiratory viruses, and to indoor air quality problems generally, where instead of a single solution there must be layers of protection providing varying levels of function, or multiple layers to inhibit the risk porosity. In terms of contaminant - in this case a respiratory virus, there should be enough layers so there is little chance perforations align and transmit disease in an indoor environment.

## The Swiss Cheese Pandemic Defence Model

While a layer model is very useful it does present challenges; the first is the kind of porosity that exists within the layers, for example in masks. Obviously if people don't wear a mask properly, then they are not going to be particularly effective - and this also applies to ventilation and air cleaning. It must be done correctly to make a substantive difference in transmission rates. Secondly, a space must not be assessed and treated in isolation as a control variable, as people interact within different spaces both inside and outside of a building over the course of a day.



## The Swiss Cheese Respiratory Virus Pandemic Defense



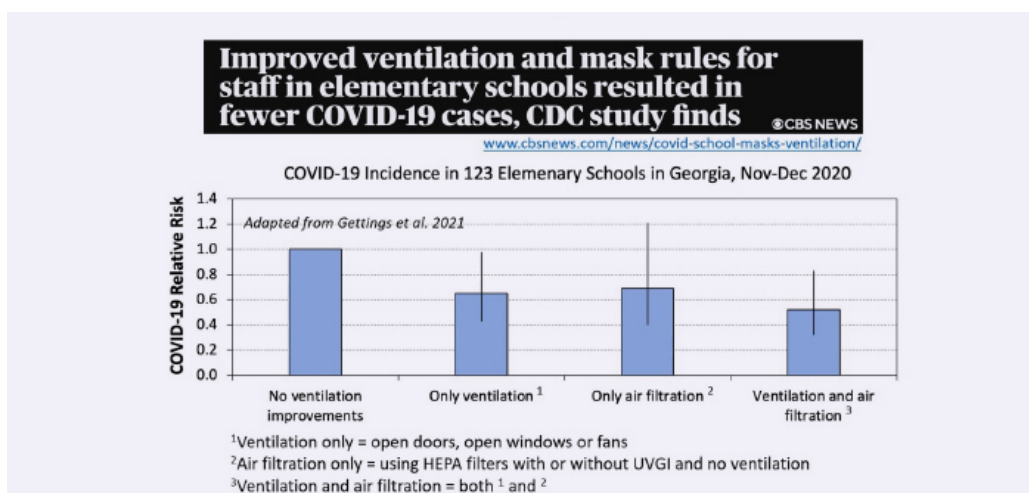
"There is no definitive single solution to this issue, eradicating COVID viral particles requires a universal approach..."

The salient example are school environments where health protocols suggest that people remain exactly two meters apart from each other. In the classroom where congregation occurs in crowded hallways and classes, the whole possibility of a transmission chain must be addressed. While the discussion dwells predominantly on-air cleaning and filtration, ventilation is the primary focus. To be clear in terms, ventilation means fresh air from outside, and filtration means air that is recirculated from the same space or from other spaces in a building

### Ventilation and Filtration

There are types of air cleaning or filtration approaches that remove infectious respiratory particles or contaminants, and they can be central or room based. There is no definitive single solution to this issue, eradicating COVID viral particles requires a universal approach, and these must be executed efficiently so that measures make an actual difference.

### Ventilation and air cleaning reduce COVID risk



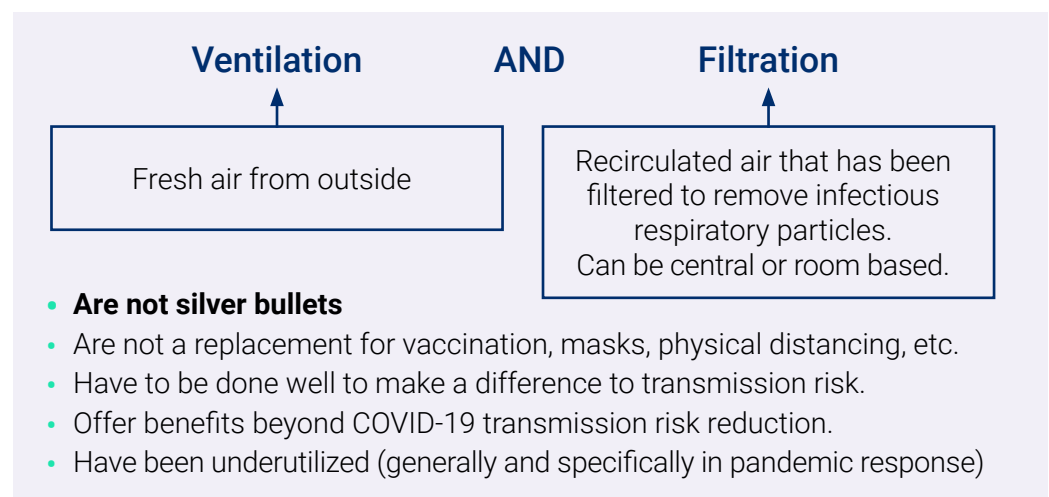
Source: Gettings et al. 2021, CDC MMWR Vol. 70, May 21, 2021



## Are Our Buildings Making Us Sick? continued

In terms of an evidence base, a study from Fall, 2020 in Georgia looked at the incidence of COVID cases in the state's schools, with comparisons to schools with ventilation and without. Ventilation or filtration alone or together show a lower risk when applied, and whilst this study doesn't have a lot of specificity the overall point is that these measures not only work for COVID-19, but also for a variety of other issues. There has been more scientific research conducted in test chambers and in controlled environments, and observational epidemiological data shows both ventilation and filtration are effective at a fundamental level. What does it mean to do these competently? Good ventilation should be provided as much as possible without compromising other environmental concerns in buildings. Namely the occupants' comfort particularly around humidity and temperature, as well as avoiding the transfer of pollutants from outdoor air to indoor ventilation.

### Ventilation and Filtration



The downside of good accessible ventilation is the associated energy consumption, which can have quite high consequences especially in more extreme climates. In addition to supplying heated or cool air, cleaning and filtration approaches must be considered when proposing additions to ventilation. An important point to note is that it's not just the filter that matters, it is also the context. The main aim is to remove pathogen from the air, whether it be a respiratory droplet containing the virus or some other particle, by getting it to the filter before someone else breathes it in and fit into the entire picture of the building.

### Filtration: Context is everything

Filters can be complicated as there can be a difference between the filtration efficiency expected and what actually occurs. For example, in terms filter efficiency where 100% means perfect efficiency, a study of 420 homes in Toronto shows that when the same brand-new filter was installed only some of these homes were achieving high efficiency from this filter. Other homes were showing a much lower efficiency, which clearly indicates the importance of not only addressing the filter piece, but the broader system. There are reasons for the variation between buildings, one example is something called a bypass. A commercial building in Montreal containing a whole filter rack in the mechanical room showed small gaps around the filter leading into the rack, and large gaps where the filter extruded. So again, the efficiency of that filter becomes much less important than the paths for air to circulate.

In regard to filters and lifetime use, evidence from a commercial building in Finland showed that modern filters made of electric or charge media filters declined over time. This indicates that a new filter starts out performing quite well - and this includes some of the higher efficiency filters, but after only three months the level of filtration declines substantially. The question is how can this decline be effectively addressed? The primary outcome for air health ventilation means getting as much ventilation as possible into a space without compromising other goals. A central filtration system means that a good filter is paramount, and ensures that air streams through it without compromising direct flow ie. gaps and changing over in a timely manner.



## What does ventilation well mean?

### As much ventilation as possible without compromising

- Comfort
- Humidity
- Temperature
- Outdoor pollutant transfer

### Energy consequences can be very large

- Opportunities for smart ventilation
- Consider supplementary air cleaning

“...data shows clearly that when indoor air quality is improved in schools there are a variety of desirable outcomes.”

From an economic perspective indoor air quality has variables in different types of environments, for example schools. And at this point data shows clearly that when indoor air quality is improved in schools there are a variety of desirable outcomes. Data collected from office buildings shows the benefit to cost ratio when investing in different filter efficiencies. Studies have shown that returns on investment in filtration are between 10 and 100 to one in office buildings.

The main return on that investment arises from avoided health care costs and a variety of other productivity and benefits also have genuine economic value. To be definitive, effectiveness can be assessed in a quantitative way, where the ultimate aim is to achieve effective air cleaning interventions. Simply put, it's the percent reduction of contaminant in a space due to the operation of an air cleaner or a suite of interventions intended to reduce the concentration that is pertinent to the application. In cases where respiratory viruses with an air cleaner operating are observed, and the concentration of those respiratory viruses without the air cleaner operating, a percent removal and the effectiveness of the intervention can be measured. This is a useful metric as it allows a quantitative comparison across different sets of intervention, and establishes an absolute understanding when applying interventions within a risk evaluation framework.

## Doing Ventilation and Filtration Well

### Ventilation

As much ventilation as possible without compromising

- comfort
- humidity
- Temperature
- Outdoor pollutant transfer

### Central Filtration

- Install a good filter properly
- Make sure lots of air goes through it
- Change it when needed
- Avoid unproven technologies

### Room Filtration

- Use filter with high clean air delivery rate (CADR)
- Address noise
- Place appropriately
- Change filter when needed
- Avoid unproven technologies

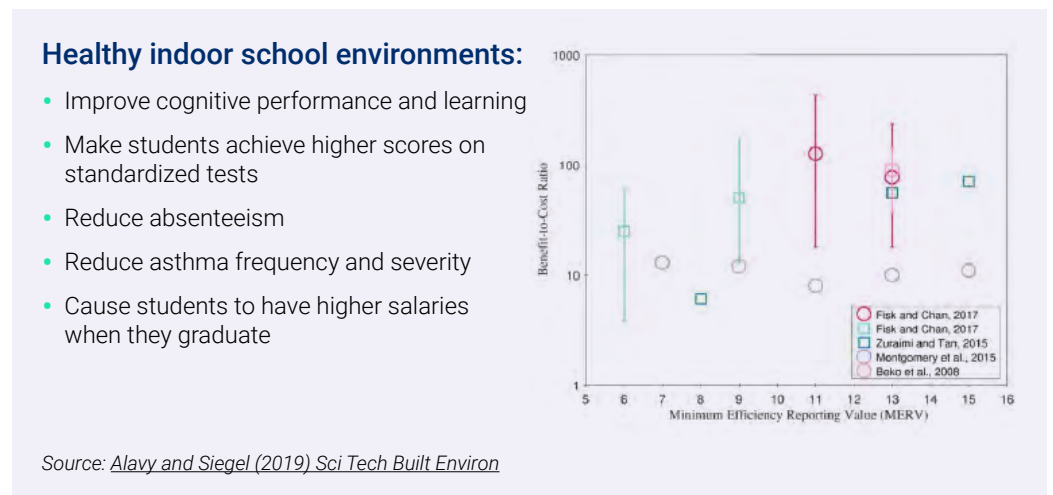
The effectiveness of an intervention or set of interventions is ultimately determined by the strength of the processes that remove a constituent in the said space. When applied generally, there are roughly four ways that it might be removed from the space.



## Are Our Buildings Making Us Sick? continued

1. It may be ventilated out of the space.
2. Flushed with clean outdoor air.
3. Hazard removal by a filter.
4. Particle deposit onto surfaces inactivated by an additive.

### Economic Rationale



Regardless, all of these processes can be applied on a common basis, following air changes per hour or the equivalent. In a typical building where there are three of these processes occurring, one air change per hour will suffice. This is an example of air cleaning in a typical space but can vary substantially, although these are reasonable values that may exist inside a building. The goal is to increase intervention effectiveness or to increase the removal of some constituent by providing additional air cleaning and or enhanced ventilation. The idea is to boost the equivalent air changes per hour, and at some layer in the space reduce the concentration of the constituent. Understanding these processes in a quantitative way is valuable as that they can be applied to high-risk spaces. Mass balance models may be able to predict what's happening in a space, and by using an engineering expert in spaces that require a designed intervention, these calculations can be applied. In a hypothetical scenario where the accumulation of an infectious virus in one Micron particle, in a space where there is one air change per hour equivalent, the important take away is that infectious viral particles will accumulate to much higher concentrations when there is lower ACH equivalent. Correct calculations can predict what is present in this space, and impact the increase of air changes per hour and the equivalent in air cleaning and ventilation. This can be achieved to 80% by boosting the ACH equivalent from one per hour to six per hour. The preferable goal is to increase that to as high as possible and calculate the intervention effectiveness from these design equations.

The goal is to boost the ACH equivalent in a space, and clearly more is better. Pushing this method to higher and higher levels of ACH equivalent and reducing the concentration of respiratory viruses is limiting and can be adverse to what can practically be achieved. **A reasonable threshold is a constant target to aim for in the vicinity of four to six air changes per hour of equivalent clean air.**



## Suggested targets for ACH<sub>eq</sub>

“The ASHRAE 170 standard which targets hospital environments, requires a minimum of six air changes per hour of equivalent air cleaning from a combination of outdoor air infiltration on supply air cleaning.”

Achievable using a combination of outdoor air ventilation and air cleaning

**TARGET IS AT LEAST 5 TOTAL AIR CHANGES PER HOUR**



**Harvard Healthy Buildings<sup>1</sup>:**  
4-6 h<sup>-1</sup>

Source: [schools.forhealth.org/wp-content/uploads/sites/19/2020/08/Harvard-Healthy-Buildings-program-How-to-assess-classroom-ventilation-08-28-2020.pdf](https://schools.forhealth.org/wp-content/uploads/sites/19/2020/08/Harvard-Healthy-Buildings-program-How-to-assess-classroom-ventilation-08-28-2020.pdf)

### ASHRAE Standard 170:

Min. 6 h<sup>-1</sup> total (OA +SA with MERV 14)  
[Min. 2 h<sup>-1</sup> from OA]<sup>2</sup>

Source: <sup>1</sup> Allen et al. 2021 JAMA 325(20): 2112-2113; <sup>2</sup> ASHRAE Standard 170-2017

This assertion arrives from groups like the Harvard Healthy Buildings Group who have already discussed this rationale for a variety of spaces. The ASHRAE 170 standard which targets hospital environments, requires a minimum of six air changes per hour of equivalent air cleaning from a combination of outdoor air infiltration on supply air cleaning. But the underlying reason for these recommendations is that boosting the ACH equivalent in a space realizes the high effectiveness of that intervention. One approach may be to boost the ACH equivalent in a space or in air cleaning technologies, which can involve varying design considerations for air cleaners.

## Avoid Certain Technologies: Additive vs Subtractive

But prefacing that, there are essentially two categorizations of air cleaners; subtractive technologies and additive technologies.

## Types of Air Cleaning Technologies

### "Subtractive" technologies

- Mechanism of action: removing or inactivating targeted contaminants from indoor air when they come in contact with the technology

Examples: filters, electrostatic precipitators (ESPs), sorbent media (for gases)

#### Key parameters

- Airflow rate
- Airflow relative to volume
- Single-pass efficiency
- Potential for byproduct formation (e.g., O<sub>3</sub> with ESP)

### "Additive" technologies

- Mechanism of action: adding constituents to the air to remove particles, inactivate microorganisms and/or react with chemical contaminants

#### Key parameters

- Type, concentration and dose of additives
- Residence time
- Potential toxicity of additives
- Potential for byproduct formation (particles/gases)

**Many air cleaners use a combination of technologies!**

Source: <https://www.epa.gov/indoor-air-quality-iaq/guide-air-cleaners-home>



## Are Our Buildings Making Us Sick? continued

Subtractive technologies are those that remove or inactivate a contaminant when it encounters the technology. A prime example is a mechanical filter that separates a particle from the airstream, and subtracts it from the air into space. Contrast that to additive technology where intentional and continuous injections of a constituent are streamed into the occupied space with the goal of trying to initiate a reaction that causes some beneficial effect. It might cause agglomeration of particles and have them settle out of the air faster or, it might initiate some chemistry that oxidizes a volatile organic compound. Many air cleaners use a combination of these technologies so in practice it might be difficult. To completely disaggregate one particular device means that it may contain both subtractive and additive technologies. It is important to have this as a key distinction in terms of the underlying mechanism in air cleaner operation. Practical considerations in subtractive air cleaners or for a portable air cleaner that's based on a mechanical filter, require a good design basis to select portable air cleaners based on mechanical filtration to appropriately size them for the space.

One of the more common test methods the AC1 results in a metric called the clean air delivery rate or CADR. Essentially the volumetric flow rate of clean air emanating from a filter in a portable air cleaner results in a CADR or freedom units. Freedom units in cubic feet per minute in clean air emanating from the space can be calculated to the equivalent air changes per hour that's realized in the space. The CADR divided by the volume of the space times 60 is the equivalent air changes per hour provided to the space. The CADR should always be provided to the consumer by the manufacturer. All recommendations for application should be followed when sizing air cleaners for a space. Ideally at least two thirds of the floor area in a space should be served. This requires an order of five per hour of additional air changes per hour of air cleaning, which means multiple air cleaners need to be deployed in larger spaces. To do this fairly confidently the design basis must be sound.

In relation to induct air cleaning, the accepted procedure is to approximate the boost and equivalent air changes per hour of air cleaning provided from induct subtractive systems. For example, from a mechanical filter placed in the supply air of a building, a single pass removal can be estimated from efficiencies like the MERV rating of a filter with appropriate caveats. Then calculations can be made to estimate what level of air cleaning is provided by that intervention. Results of research that estimate the removal efficiency of viral particles as a function of a MERV rated filter – with the influenza pathogen, shows that a Merv 13 filter has a single pass removal efficiency of 80 or 90%. For a typical commercial building supply air flow rates range from around .3 to 1 cubic foot per minute per square foot.

Combining that result with a single pass removal, the efficiency of that filter can then be selected, and the amount of clean air in the supplied filtered air flow rate can be approximated. Clearly these numbers should be sought when evaluating suitable interventions for clean air flow in a building. A design engineer can provide the desired result and application by calculating the order of 1.4 to 4.8 equivalent air changes per hour for an intervention, where the correct filtering can be applied to the air supply system of a commercial building.

### What about additive systems?

There has been substantial interest and aggressive marketing for additive systems. These systems intentionally introduce a radical hydrogen peroxide approach and can include any other number or any combination of those of disinfecting substances. Some test data for these kinds of devices do exist, and generally follow similar ideas in test methods like the AC1. The idea is to inject a test contaminant like a pathogen and watch how quickly it decays with and without the air cleaner operating. However, these tests are non-standardized and the results can be difficult to interpret, as they involve systems that intentionally introduce reactive species by product formation. There's little data in peer reviewed literature and the manufacturer provided data requires some work to interpret. Part of that is because the kinds of studies seen right now, although more are emerging, are graphics. For instance, a Boeing test report conducted in an office where an ionizing air cleaner was placed on a wire rack with a stand fan behind it, pushed out the ions generated from the space in a typical office environment delivers limited data.





The data gathered to date shows generally a small outcome of effect for additive systems. The addition of ions into a test chamber caused agglomeration and changes in the rate at which particles settle from the air in the chamber. The results show the normalized rate of decay of particles with and without an air cleaner operating. With the air cleaner or the ionizer on and off, showed that the boost and AC H equivalent from the operation of an ionizing air cleaner is minimal. Another study that emerged recently looked at whether there's an impact on single pass removal efficiency due to the release of ions into the HV AC system. They showed that there can be a small boost to infiltration due to the introduction of ions, but only for some of the higher Merv electric filters. The result from that study was that there was a change in a single pass removal efficiency through a filter, but that the change occurred due to the presence of ions. A Merv 8 filter saw a small change, Merv 10 and Merv 13 filters saw a change of a 10% boost to the single pass removal efficiency and additive systems saw a change as they intentionally introduce reactive species.

Particular attention should be paid to product formation for all interventions, especially when additive systems intentionally initiate chemistry. There are studies emerging that show it's a concern in some cases. In a study that tested four air cleaners which included additive systems and included an air cleaner that combined a UVC disinfection system, a negative ion emission source and activated carbon which is a prime example of a combination of systems; a volatile organic compound called limonene - a ubiquitous compound in indoor environments, was intentionally injected and the decay monitored. The air cleaner showed a modest increase in the rate of removal, but at the expense of forming formaldehyde particles and an increase in the total VOC. When systems change the chemistry that occurs in a space the challenge is to interpret the results of nonstandard air cleaner test data and additive systems, which can be difficult to interpret in terms of the effect in a space.

For instance, a marketing statement for an air cleaner may assert a reduction of viable SARS Co V2 by 99% in thirty minutes, which is simple to interpret, but does requires some translation to try and understand. How did that test result come about? How was that test result achieved, and what does it mean in the space where the air cleaner is to be installed? A hypothetical test result may show decay data where a target pathogen is being removed under control conditions. An air cleaner operating and instigating separation and fast removal of a pathogen at one hour where the concentrations are reduced by 99% - is where the marketing statement originates. But as this is not a test chamber, how does the statement translate that into a full-scale environment? This is a relevant question that should be asked when assessing systems for the buildings that need clean air supply.

What do those test results mean when installing this device for a space? What is the key variable that it's dependent on.? Another example is a test conducted in a 100 cubic foot test chamber, where the result was that the clean air delivery rate was only 1.5 CFM - very low, almost negligible; and in a 10,000 cubic foot space only realized a .01 per hour of boost in AC H equivalent. If it was a 100 cubic foot chamber, those numbers go up by order of magnitude; similarly for 1000 cubic foot chamber, another order of magnitude. The key concern is: how was the test conducted? What were the results, and how are they scaled to the environment when seeking to install an air cleaner. Unfortunately, the guidance from authoritative agencies such as the Centre for Disease Control have largely left these calculations up to the individual. The Centre for Disease Control has a FAQ where they do say that many new air disinfection devices are marketed for their ability to inactivate SARS Co V2. How does the consumer know if they work as advertised? The answer is basically that consumers are encouraged to do their homework on the devices, so evidently there is gap in interpreting this data. A spreadsheet tool has been developed to help make this translation easier, the air cleaner efficacy investigation tool (ACEIT) and can help in understanding how air cleaner test data is presented in the form of 99% reduction in an hour, and how that might translate into the AC H boost in a space.

**“Practical considerations in subtractive air cleaners or for a portable air cleaner that's based on a mechanical filter, require a good design basis to select portable air cleaners based on mechanical filtration to appropriately size them for the space..”**





“Air cleaning can be one part of the COVID toolkit”





# Conclusion

Air cleaning can be **one part** of the COVID toolkit:

**Building systems can protect occupants through some combo of:**

- Increased outdoor air
- Improved filtration/disinfection in central system
- Portable air cleaning (including UVGI placed in room)

**Mechanical filter-based air cleaners have clean air delivery rates that can increase removal of viral pathogens from indoor air**

- If appropriately sized

**Many options and aggressive marketing for air cleaners**

- Independent verification of air cleaner performance is necessary

**Air cleaner test data reports**

- In form usable by engineers/facility operators, building owners and general public

“Mechanical filter-based air cleaners have clean air delivery rates that can increase removal of viral pathogens from indoor air.”





## Conclusion continued

To sum up air cleaning can be just one part of a COVID prevention toolkit. Building systems can protect occupants through a combination of approaches, increasing outdoor air supply when possible, filtration and disinfection in the central system and portable air cleaning place throughout the room from mechanical filter based air cleaners. The ability to estimate cleaner delivery rates and evaluate the effectiveness of those interventions through relatively routine calculations is essential to success. For other options and for the ablative air cleaners that are being aggressively marketed, independent verification of air cleaners in general is needed, as are performance data and tools to understand how that might be translated into the performance in the space. Air cleaner test data should be in a form that's usable by not just engineers and facility operators, but building owners and the general public.

### **We understand the need and how we can implement these systems, but where and how do we get them and what do they actually look like?**

West Haven, Santé and our team of engineers and researchers have done extensive research in trying to narrow down the field to units that actually work. We need to study the test data, so extensive testing has been done on these units to prove that they do work. In a typical portable HEPA filtration unit there is a 360 degree air intake at the bottom which pushes up through a fan and then further pushes that air up through a three-stage filter. A F7 pre filter can take volatile organic carbons out of the air, as does a carbon filter and a true H 13 HEPA filter.

It's important to note that whatever air goes in into the unit needs to be purified and special attention applied to ensure there is a zero particle count. To elaborate, filters need to be safe. Once they are removed there should be no risk to the user of contamination, and that no medical waste is being produced so that these filters can be dispose of safely. Furthermore, the expectation from a unit is that it has its own inbuilt smart air quality monitor. This is a particle sensor that senses the current particulate matter in the air. Our particular unit has a PM 2.5. and adjusts the fan speed accordingly. If there was an incident where there is a higher particular load in the room, the fan speed needs to be increased.

If there is good air quality there is no need to expend unnecessary energy an additional positive function is that units have connectivity to an app or fleet control system to prevent this. The Aeris unit which is Swiss engineered, can actually remotely control multiple units. current air quality, speed, filter life and the actual location of the units.

Another important point to consider is the total lifespan of a filter. Typically, Aeris filters have a 12-month lifespan whereas domestic units on the market will often only have about a six-month lifespan, regular filter changes which is a major operational expense. The unit must also have a reliable fan, as typically most units are simply constructed with a fan and a HEPA filter. The Aeris, available through West Lab and Santé, two products are flagged. The Air Light which can handle up to four changes per hour in a 30 square meter or 350 square foot space, is a compact unit, can sit in relatively small office spaces and is unobtrusive. It can handle air in a apace space of up to 70 square meters and is suitable for educational settings, canteens areas and larger gathering points within an organization. In terms of connectivity a typical app can moderate both indoor air quality and feed in from a local EPA. In an event such as a bush fire or high pollen load, it would actually increase fan speed and improve air quality.

A more economical version is Zonitize, a simple and slightly smaller unit, but powerful in its own right. This unit contains a mechanical filter and has no UV or ionization technology. The consensus is that HEPA technology is the most beneficial way forward in air filtering, and the Zonitize gives volumes of up to 600 cubic meters per hour of air flow and typically three to four air changes per hour.



## Panel Questions

Doctor Jeffrey Siegel and Doctor Elliott Gall

### What are the pitfalls of an ionization system, and what can you say about UV?

UV is a time-tested technology. It can work very well in either in duct configuration or upper room configuration near the ceiling, and can be another layer of protection. UV only treats microorganisms, so other aspects of indoor air quality will not be treated. There is a question about sizing for UV, and if it is effective in to deliver enough ultraviolet light in the brief time that the microorganism is illuminated. UV is an approach that should not be undertaken casually. It must be applied properly and designed to make a difference. An engineering firm should be engaged to install an UV system, whether it's upper room or in a ducted system, and can be effective in pathogen inactivation.

### What are the pros and cons of central filtration versus portable? And how does it affect airflow in existing buildings?

The general recommendation is to avoid placing a portable air cleaner in a corner of a room with the outlet directed towards a wall. Best practices should allow the outlet to have sufficient velocity which will send air upward and mix it into the space. It can become a complex decision as to placing the air cleaner for maximum effectiveness. Essentially the air cleaner should be in a space where it is not intentionally inducing air flows that might move from one person towards another. Upward facing outlets can help by sending flow into the well mixed core of a room.

### Is portable or central filtration better?

They're both viable options, but the decision is driven by context. For example, some buildings would like to put in better filters but cannot because of the age and the design of the system. Some spaces require the flexibility of portable air cleaning, like a break room where people are eating and likely to be unmasked and closer together. This poses a higher risk and is therefore a good environment to include a portable unit.

### What is the misconception about HEPA filters filtering out CO<sub>2</sub>

Definitively HEPA filters do not filter out CO<sub>2</sub> - that's very clear. But there is a wealth

of information regarding indoor air quality monitoring, and it really needs to be done well to provide actionable information. For example, if a sensor is placed in a dead space in an indoor environment, it must provide actionable information; therefore, it's essential that sensors are placed appropriately to understand what they mean. CO<sub>2</sub> monitoring and particle monitoring can very useful in a relative sense, that is, if a room usually sits at a reasonably low concentration of CO<sub>2</sub> and suddenly it goes to a much higher concentration of CO<sub>2</sub>, that indicates that something has changed and must be addressed.

### Can monitoring specific safe or unsafe thresholds via relative understanding of the space be done?

It might have high uncertainty, but it is possible. It is a different scenario to CO<sub>2</sub>, but particle monitoring can be very useful for understanding relative changes in the space and can give a good idea of the effectiveness of an intervention. In an air cleaning intervention, just like the portable air cleaners in a break room, crude experiments would probably show around an 80% effectiveness. CO<sub>2</sub> can act as a proxy measurement for air quality and then when intervening with a low-cost particle monitor, results can then show substantial reductions in particulate matter, which indicate whether the intervention has succeeded.

### Do you actually see substantial reductions in particulate matter with a low-cost particle monitor?

It's not directly related to particulate matter in the air they but they can monitor parameters such as radon, VOC'S, etc.

### Any comments on that? Perhaps on some of the other measures out there?

CO<sub>2</sub> is a metric that's been measured in buildings for a long time and there are relatively low-cost sensors that can do that. In the past decade or so, lower-cost particle counters have come online and can also measure particulate matter in a space for volatile organic compounds. Measurements that come out of some of the lower cost VOC measurement devices can be a little more difficult to interpret.

**"Some spaces require the flexibility of portable air cleaning, like a break room where people are eating and likely to be unmasked and closer together."**



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