Effectiveness of Air Cleaners for Removal of Virus-Containing Respiratory Droplets:

Recommendations for Air Cleaner Selection for Campus Spaces

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Introduction

Portable air cleaners (ACs) are used to remove airborne contaminants from indoor air. ACs are typically used to remove particulate matter (PM) such as dust, pollen, and smoke; and gases such as nitrous oxides, radon, and volatile organic compounds (VOCs).[1] Right now, air cleaners are being considered as a method to capture airborne respiratory droplets containing the SARS-CoV-2 virus. Respiratory droplets can stay suspended in the air for up to an hour or more depending on the droplet size and room currents[2], so removing them with an air cleaner is a reasonable strategy to add to the suite of public health methods deployed to reduce virus transmission. Furthermore, improving air quality reduces risk of respiratory disease in general. There is a wide range of air cleaners on the market today, and many people are asking how to choose an air cleaner that is best suited for removing virus-containing droplets? Air cleaners in the USA are characterized by their clean air delivery rate (CADR) and recommended room volume, so the first section of this report will begin by discussing air cleaner CADR and effectiveness, and how those metrics relate to the room volume. The next section will present the different technologies of air cleaners available on the market, discussing their effectiveness and secondary effects. Finally, specific air cleaners will be recommended for use in different sized rooms on the CU campus.

Air Cleaner Performance Metrics

Clean Air Delivery Rate (CADR)

Single pass efficiency is the most basic way of describing an air cleaner's performance. The efficiency depends on the air cleaner design and contaminant being treated. For particulate pollution applications, the efficiency is a function of particle size and reports the fraction that is captured by the cleaner in a single pass of the airstream through the device. This is a useful metric for devices where the air only passes through one time, such as in air cleaning technologies used to clean gases being released from industry exhaust stacks. An important metric for ACs is the flow rate, because even if an AC has a high efficiency, if the flow rate is very low, it will not effectively clean the room. The inverse is also true; a reasonably effective AC with a high flow rate *can* effectively clean a room. Plus, single pass efficiency does not consider mixing and re-entrainment of the clean air.[3] To account for these considerations, the clean air delivery rate (CADR) is used to characterize air cleaners. The CADR is also given for a particle size range and it is defined as the flow rate of air that has had all the particles of that range removed. CADR is a widely used metric to characterize air cleaners and is widely used in both industry and in research.[4–6] It is the product of the AC's single pass efficiency and its flow rate and is normally given in cubic feet per minute (cfm). The Association of Home Appliance Manufacturers (AHAM) tests and certifies air cleaners for three types of particles: smoke (0.09 – 0.1 μm), dust (0.3 – 3 μm), and pollen (5 – 11 μm).[7] To determine the CADR, experiments are conducted and the data is interpreted with a 'well-mixed box' model, where it is assumed that the concentration of pollutants in a room is well-mixed and therefore uniform. This is described by the material-balance equation:

$$\frac{VdC_i}{dt} = QC_o - QC_i + S - kC_iV \qquad \textit{Eq. 1}$$

where V is the room volume, C_i is the indoor pollutant concentration (mass/time), Q is the room ventilation rate (volume/time), C_o is the outdoor pollutant concentration (mass/time), S is the source emission rate (mass/time), and k is the pollutant removal rate (1/time). The CADR test is performed in a chamber with negligible ventilation so Q is set to zero and C_o is also zero. The pollutant is released into the room and mixed into the space before beginning the CADR test, meaning that S is also zero. The removal rate, k can be broken down into the mechanisms by which pollutants are removed from the air: $k = \lambda_v + \lambda_d + \lambda_{AC}$, where λ_v is the removal rate by infiltration, λ_d is the removal rate by deposition, that is particles naturally dropping out of the air due to gravity, and λ_{AC} is the air cleaner removal rate and these have units of 1/time. The change over time of the pollutant's concentration is measured, once with the air cleaner running and then the test is repeated without the air cleaner to determine the infiltration and deposition rate. The decay of the pollutant concentration with and without an AC is shown in Figure 1. This means that the CADR accounts for only the particles captured by the cleaner but not those that were deposited onto surfaces in the room or removed by infilration. CADR is given as:

$$\text{CADR} = V(k_{AC} - k_{noAC}) = V(\lambda_v + \lambda_d + \lambda_{AC} - \lambda_v - \lambda_d)$$

Eq. 2

$$CADR = V\lambda_{AC}$$

where k_{noAC} is the pollutant removal rate when the AC is not running. The range of CADR that the AHAM uses in its certification program is 10 – 450 cfm.

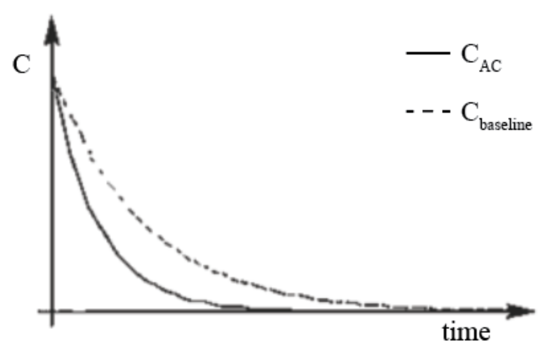

Figure 1. Concentration of pollutant as a function of time with and without an AC operating. [8]

Effectiveness

Once the CADR has been measured, one needs to determine what is an acceptable value of CADR given the volume and ventilation rate of the room and the size of particles to be removed. The metric that takes this into account is the effectiveness, which is the ratio of the air cleaner's removal rate to the baseline removal rate by deposition and room ventilation only.[8] It describes how well the air cleaner removes a pollutant compared to other typical removal processes and is given by:

$$\varepsilon = \frac{C_{baseline} - C_{AC}}{C_{baseline}} = \frac{CADR}{V(\lambda_v + \lambda_d) + CADR} \qquad \textit{Eq. 3}$$

where $C_{baseline}$ is the pollutant concentration when the AC is not running. An effectiveness of 1 is the ideal performance, where the air cleaner has removed all pollutants. The AHAM recommends an effectiveness of 80%, which essentially means that the air cleaner provides 5 air changes per hour of pollutant removal, or that the CADR normalized to the room volume = 5 1/hour.[3] A typical air cleaner certificate from the AHAM is given in Figure 1, showing the three CADR values and the recommended room area, which assumes a ceiling height of 8 feet.

Figure 2. AHAM Verifide certificate showing the CADR values and room area for a Blueair – 580i air cleaner. (Note: the authors believe that there is an error on the certificates from the

AHAM website. The room area quoted is in square meters, not feet. AHAM has been notified of this error.)

The CADR and effectiveness of air cleaners is tested for three types of particulate matter, smoke, dust and pollen, but are these metrics also applicable to respiratory droplets containing virus particles? There have been several studies exploring the effectiveness of different types of ACs on removing or inactivating airborne bacteria and fungal spores,[4] bio-aerosols,[9] virus particles,[10] and tuberculosis-type bacteria.[11] Miller-Leiden et al.,[11] Shaughnessy et al.,[12] and Foarde[9] have reported that there is agreement between airborne biological and nonbiological particulate matter removal by air cleaners; if particles have a similar aerodynamic diameter, they will be filtered with similar effectiveness regardless of whether or not they contain bacteria or viruses. In a recent study on the respiratory droplets from a common cold, Lee et al.[2] determined that most particles have diameters smaller than 5 μm. This means that respiratory droplets fall within the size distribution of the particles tested by the AHAM. This would suggest that the CADR for dust and smoke can be used to determine the ability of an AC to remove virus particles.

Cumulative Clean Mass (CCM)

CCM is an indicator of total mass of target pollutant (particulate matter and/or gaseous pollutants that the appliance can cumulatively purify in rated condition and specified test condition. The mass is weighted when CADR of the appliance decreases to 50% of its initial value.

This CCM (mg) index, together with CADR, represents how effective an air cleaner can clean the air because CADR only represents how much air can be treated by the device. The higher the CCM, the more efficient the device. CCM can also be linked/converted to another index "Cleaning Life Span" (days) of an air cleaner, and thus is important to evaluate the frequency of filtering change, system cleaning, and product life.

Air Cleaner Technologies

This section discusses the different technologies used in air cleaners that are available on the market, explaining how the technology works, the air cleaner effectiveness for removing respiratory droplets, and finally any secondary effects. Many of these technologies are used in combination to remove different types of pollutants. Zhang et al.[1] did an extensive literature

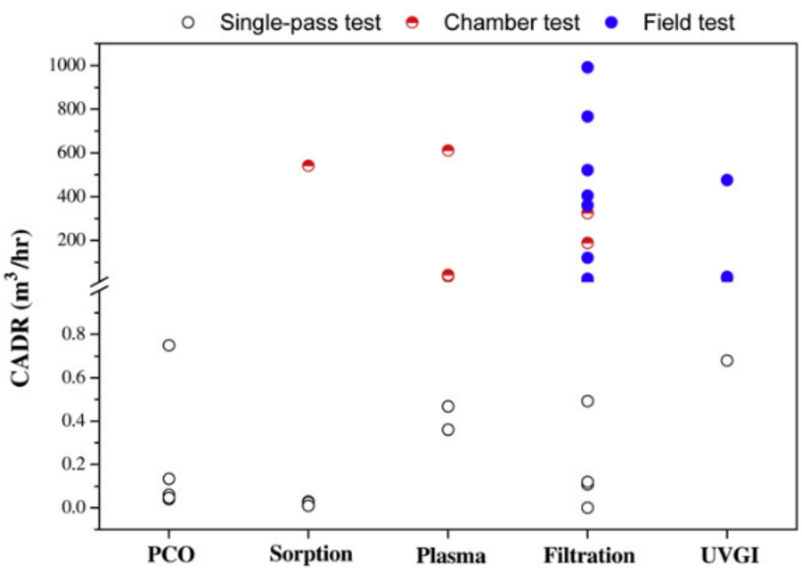

Figure 3. Summary of reported CADR m^3/h. (To convert to cfm, divide the CADR value by 1.699). UVGI refers to ultraviolet germicidal irradiation and PCO refers to photocatalytic oxidation.

review on air cleaner studies and Figure 3 shows the measured CADR values. This figure also shows which technologies have been studied the most.

Filtration

Particulate-filter air cleaners use a fan to blow air through a pleated fiber filter medium. The filter catches particulate matter mechanically by impaction, diffusion and interception, and as the particulate matter builds up, the filtration efficiency improves, up to a point. Then the pressure drop is too great, and the filter media must be replaced. Filtration air cleaners have been researched extensively, both in chamber tests and in the field[1] and it has been shown that they are very effective at removing particulate matter, including respiratory droplets.[4,11] However, filtration with particulate filters does not remove gaseous pollutants, and to do so they are commonly combined with an activated carbon filter. A very common particulate filter is the High-Efficiency Particulate Air (HEPA) filter, which means that the single-pass efficiency of the filter media is 99.97% for 0.3 µm particles.[13] A HEPA filter does increase the pressure drop across the filter, and thus the energy usage, and some tests have shown there is not a statistically significant difference between the effectiveness of HEPA filters and non-HEPA filters. To function effectively and prevent shedding of the particulate matter in the filter, the air cleaner's filter needs to be replaced periodically.[14]

Electrostatic Precipitators (ESPs)

Electrostatic precipitators are commonly used to remove fly ash and dust from the exhaust of power plants and industrial processes, but they are also being used in portable ACs. In an ESP, the air stream is first ionized by flow between electrically charged plates which emit corona. The air stream flows through a second pair of plates to which the charged particles stick and are then removed. ESPs effectively capture particulate matter, and the corona inactivates biological particles. However, ozone is formed by the corona, which can then cause ultrafine particle formation and gas-phase pollutant by-products, which are all health concerns. ESPs need to be cleaned often to keep ozone production to a minimum.

Catalytic Oxidation

Photocatalytic oxidation (PCO) is used to treat gas-phase pollutants and degrades many contaminants by passing the airstream through a catalyst. In single-pass tests, PCO effectively removes VOCs, odor compounds, and alkanes, along with other contaminants.[1] However, the formation of by-products such as formaldehyde is a critical issue for catalytic oxidation.[15]

Plasma

Plasma, an ionized gas, is generated by corona discharge, direct current, and dielectric barrier discharge.[1] The plasma ionizes pollutants, which make them easy to oxidize and thus 'neutralize'. In general, plasma technologies can enhance the performance of filters for particle removal and catalysts for gas-phase pollutants. However, the production of secondary pollutants such as NO_x, formaldehyde and O_3 is a major drawback of plasma technology.[1,14]

Adsorption

Adsorption is the mechanism by which gas molecules stick or adsorb to the surface of a porous solid. Activated carbon is typically used as the adsorption medium in air cleaners. This technology works well for gaseous pollutants such as volatile organic compounds (VOCs) and ozone. However, there is a possibility that the sorbed gases could generate by-products.[14]

Germicidal Ultraviolet light (GUV)

Ultraviolet (UV) light in the UV-C range, germicidal UV (GUV), is used to inactivate microorganisms either in an air stream or within a filter. GUV lamps are often used in conjunction with other technologies, such as with filters. GUV has been shown to deactivate airborne virus, bacteria and fungi,[4] but conclusive field data are still lacking and secondary pollutants have not been studied.[1]

Air cleaner recommendations

Filtration is the recommended air cleaner technology for removal of respiratory droplets in offices and classrooms on the CU campus for the following reasons: (i) filtration is the most studied air cleaner technology, (ii) it has good performance for particulate matter, including respiratory droplets, (iii) many of the other technologies have the potential to emit secondary pollutants, especially ozone. Many filter air cleaners on the market are combined with activated carbon filters, which work well in conjunction with fiber-media filters as they can capture gaseous pollutants that pass through the mechanical filter.

Table 1. Recommended air filters available in the USA, organized by the type of filter

Brand	Model	Tech	Max room size (ft^2)	Smoke CADR	Dust CADR	Pollen CADR	AHAM	CARB	Cost $
Oransi	EJ120	Activated Carbon & HEPA filter	500	323	332	360	✓		899.00
Airgle	AG500	Activated Carbon & HEPA filter	369	238	239	253	✓	✓	1500.00
Winix	D360	Activated Carbon & HEPA filter	360	233	230	235	✓		249.99
Honeywell	HPA600B	HEPA filter	325	210	184	205	✓	✓	769.99
Honeywell	HPA200	Activated Carbon & HEPA filter	310	200	190	180	✓	✓	217.79
Samsung	Cube Air Purifier	Washable pre-filter, Activated Carbon & HEPA filter	310	200	205	185		✓	699.00
Braun	SensorAir Diagnostic Filtration System	Washable pre-filter and filter, Activated Carbon filter	300	200	194	190	✓	✓	446.90
Honeywell	HPA100	Activated Carbon & HEPA filter	155	100	106	100	✓	✓	153.99
Sharp	FPF30UH	HEPA filter	143	101	92	109	✓	✓	119.99
Whirlpool	WPT60	Activated Carbon & HEPA filter	104	67	86	86	✓	✓	115.99

Conclusions

In this report, the performance metrics needed to characterize air cleaners were described, and then different types of air cleaner technologies were presented. It was shown that the CADR was applicable to the effectiveness of removing respiratory droplets. Air cleaners using pleated fiber-media filters were recommended because of their effectiveness and simplicity. Further, they have been studied in great depth and no by-products have been identified. Table 1 shows several air cleaners using the recommended filter technology, ordered from largest room to smallest room use. To choose a suitable air filter for a room, one needs to ensure that the room has the same or smaller area than the maximum room size. For a larger space, such as a conference room or a lecture hall, it is recommended to use multiple air cleaners. Air cleaners are additive so if one needs to clean a 1500 ft^2 room, then 3 air cleaners that treat 500 ft^2 each will work. In practice, when specifying air cleaning devices, it is important to incorporate room air cleaners with existing room ventilation systems. As a practical rule of thumb, it is suggested to have this combination setting: 2000 m^3/h (1177 cfm) of cleaned air with 500~1000 m^3/h (294~588 cfm) of fresh air ventilation (i.e., 1 fresh air to 2~4 room circulated cleaned air). In addition, energy efficiency and noise level should be evaluated due to the continuous operation in sensible spaces such as offices and classrooms (people may easily turn it off if it is too noisy). Lastly, some air cleaner models with disinfection functions (e.g. use of germicidal ultraviolet light) should receive fair attention although testing and certification on these products has not been internationally recognized.

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