

The effectiveness of stand alone air cleaners for shelter-in-place

Abstract Stand-alone air cleaners may be efficient for rapid removal of indoor fine particles and have potential use for shelter-in-place (SIP) strategies following acts of bioterrorism. A screening model was employed to ascertain the potential significance of size-resolved particle (0.1–2 μm) removal using portable high efficiency particle arresting (HEPA) air cleaners in residential buildings following an outdoor release of particles. The number of stand-alone air cleaners, air exchange rate, volumetric flow rate through the heating, ventilating and air-conditioning (HVAC) system, and size-resolved particle removal efficiency in the HVAC filter were varied. The effectiveness of air cleaners for SIP was evaluated in terms of the outdoor and the indoor particle concentration with air cleaner(s) relative to the indoor concentration without air cleaners. Through transient and steady-state analysis of the model it was determined that one to three portable HEPA air cleaners can be effective for SIP following outdoor bioaerosol releases, with maximum reductions in particle concentrations as high as 90% relative to conditions in which an air cleaner is not employed. The relative effectiveness of HEPA air cleaners vs. other removal mechanisms was predicted to decrease with increasing particle size, because of increasing competition by particle deposition with indoor surfaces and removal to HVAC filters. However, the effect of particle size was relatively small for most scenarios considered here.

M. Ward, J. A. Siegel, R. L. Corsi

Center for Energy and Environmental Resources,
 Department of Civil Engineering, The University of
 Texas at Austin, Austin, TX, USA

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J. A. Siegel, Center for Energy and Environmental Resources, Department of Civil Engineering, The University of Texas at Austin, 10100 Burnet Road (R7100), Austin, TX 78758, USA.
 Tel.: +1 512 471 2410
 Fax: +1 512 471 1720
 e-mail: jasiegel@mail.utexas.edu

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Practical Implications

The results of a screening analysis suggest that stand-alone (portable) air cleaners that contain high efficiency particle arresting (HEPA) filters can be effective for reducing indoor fine particle concentrations in residential dwellings during outdoor releases of biological warfare agents. The relative effectiveness of stand-alone air cleaners for reducing occupants' exposure to particles of outdoor origin depends on several factors, including the type of heating, ventilating and air-conditioning (HVAC) filter, HVAC operation, building air exchange rate, particle size, and duration of elevated outdoor particle concentration. Maximum particle reductions, relative to no stand-alone air cleaners, of 90% are predicted when three stand-alone air cleaners are employed.

Nomenclature

A	Collective area of all indoor surfaces (m^2)	p	Fractional particle penetration efficiency (–)
α	Sum of particle removal factors (1/h)	Q	Volumetric infiltration rate into and out of house (m^3/h)
C	Indoor particle mass or number concentration (mg/m^3 or number/m^3)	Q_f	Volumetric flow rate of air through HVAC system (m^3/h)
$C(t)$	Indoor particle mass or number concentration at time t (mg/m^3 or number/m^3)	Q_{pf}	Volumetric flow rate of air through portable air cleaner (m^3/h)
$C(\infty)$	Indoor particle mass or number concentration at steady-state (mg/m^3 or number/m^3)	t	Time (h)
$C(\infty)_{\text{nopf}}$	Indoor particle concentration at steady-state without air cleaner(s) (mg/m^3 or number/m^3)	V	Volume of house (m^3)
$C(\infty)_{\text{pf}}$	Indoor particle concentration at steady-state with air cleaner(s) (mg/m^3 or number/m^3)	v_d	Surface-integrated particle deposition velocity (varies with particle size) (m/h)
C_o	Outdoor particle mass or number concentration (mg/m^3 or number/m^3)	η_f	Fractional removal efficiency associated with HVAC filter (varies with particle size) (–)
CADR	Clean air delivery rate (m^3/h)	η_{pf}	Fractional removal efficiency for portable air cleaner (varies with particle size) (–)
Γ	Air cleaner effectiveness relative to no air cleaner (–)	λ	Rate of air exchange between the indoor and outdoor atmospheres (1/h)

Introduction

Growing public concerns regarding acts of terrorism have led to actions ranging from government advice to reduce residential air exchange rates through selective use of duct tape, to subsequent public demands for tape products and protective breathing devices. There is clearly a need for an improved understanding of potential human exposure to chemical and biological warfare agents (BWAs) following a terrorist attack, as well as rapid-response shelter-in-place (SIP) measures that the public can take to minimize their exposure to such agents.

Stand-alone (portable) air cleaners containing high efficiency particle arresting (HEPA) filters may be effective at rapidly removing fine biological particles from residential indoor air following an act of bioterrorism, and thus serve as a tool for SIP strategies. Numerous researchers have studied the effectiveness of portable air filters for the removal of particles from residential indoor air (Antonicelli et al., 1991; Cheng et al., 1998; Emmerich and Nabinger, 2001; Green et al., 1999; Huang, 1993; Offermann et al., 1985; Wood et al., 1997). However, past studies have often focused on reductions in large particles associated with pet allergens, pollen, and dust-mites (Antonicelli et al., 1991; Cheng et al., 1998; Green et al., 1999; Wood et al., 1997). Furthermore, many of the studies related to allergens are based on implicit measures of filter effectiveness gleaned from surveys or health responses, as opposed to direct measurement of particle removal efficiency (Huang, 1993). Those articles in which changes in particle concentration before and after employment of portable air cleaners are measured, generally consider only total particle number or mass concentration, without size resolution (Antonicelli et al., 1991; Cheng et al., 1998; Green et al., 1999). Nevertheless, the effectiveness of portable air cleaners for reductions in indoor particle and allergen levels has been noted to be significant. Mean particle levels associated with dust-mites were reduced by approximately 70% following the employment of air cleaners containing HEPA filters in nine homes (Antonicelli et al., 1991). In a separate study of nine homes with dogs, commercial air cleaners with HEPA filters were able to reduce airborne dog allergen, *Can f 1*, by upwards of 90% (Green et al., 1999). By several metrics (questionnaire responses, emergency room visits, workdays missed by parents, expenditures on allergy medications, etc.), the use of air cleaners in the bedrooms of 90 children with perennial allergic rhinitis was effective.

In a study focused specifically on the ability of portable air cleaners to control particulate matter of outdoor origin, Cheng et al. (1998) studied the effectiveness of a portable air cleaner containing a HEPA

filter on the removal of pollen and fungal spores in a single-family home with different ventilation rates within the rooms where the air cleaners were located. At low air exchange rates ($< 0.2/h$) the air cleaner was observed to have a marked effect on pollen and fungal spore concentrations, with a rapid decrease (within 1 h) to $< 10\%$ of initial values. The overall effectiveness of the air cleaner decreased as room ventilation rate increased.

Several researchers have used more controlled laboratory studies to better understand the effectiveness of portable air cleaners for different types of particles (Foarde et al., 1999a,b; Shaughnessy et al., 1994). Shaughnessy et al. (1994) used a large source chamber to test various types of portable air cleaners and observed that HEPA based systems demonstrate higher efficiencies than electret filter systems, ionizers, and ozone generators for particle removal. Experiments were completed using dust particles, particles associated with environmental tobacco smoke, fungal spores, and pollen. Foarde et al. (1999b) described a test method to determine the clean air delivery rate (CADR) for a portable air cleaner challenged with a microbial aerosol. The method was a modification of the Association of Home Appliance Manufacturers (AHAM) Standard AC-1 *Standard Method for Measuring Performance of Portable Household Electric Cord-Connected Air Cleaners*, which focuses on determination of CADR for three types of particle classes – smoke, dust, and pollen. These protocols rely on chamber testing and particle decay in the absence and presence of an air cleaner. Foarde et al. (1999a) also developed a method to measure single-pass microbial particle reduction using a portable air cleaner. The method was tested on two bacteria, two fungi, and a virus, which collectively encompasses the range of particle sizes associated with BWAs.

In this study, we developed a model to assess the potential effectiveness of portable air cleaners as a rapid response SIP tool. For the purposes of our analysis, we consider SIP strategies to affect the entire volume of a residential dwelling, as opposed to a single room. Both steady-state and transient conditions were considered. The competition between portable air cleaners, building air exchange rate, removal by filtration in heating, ventilating and air-conditioning (HVAC) systems, and particle deposition was explored. The effectiveness of portable air cleaners was characterized by the ratio of indoor particle counts in different size ranges for cases involving zero to three air cleaners. The assessment was facilitated by using experimentally determined size-resolved CADRs for common residential HEPA air cleaners. Descriptions of the model development, parameter estimation, and assessment results are presented herein.

Model development

A model based on both transient and steady-state conditions in a well-mixed residential dwelling was employed for this assessment. A description of resulting mathematical equations and parameter selection are described in this section.

A particle mass (or number) balance for a residential dwelling is presented in Equation 1.

$$V \frac{dC}{dt} = pQC_o - QC - \eta_f Q_f C - v_d AC - \eta_{pf} Q_{pf} C \quad (1)$$

The term on the left-hand-side of Equation 1 represents the change in particle mass (or particle number) as a function of time. The first two terms on the right-hand-side (RHS) of Equation 1 represent particle penetration into the home via infiltration from the outdoor atmosphere and particle exhaust from indoor to outdoor air, respectively. The third term on the RHS of Equation 1 represents particle removal by filtration in an HVAC system. The fourth term represents particle removal by collective deposition mechanisms on indoor surfaces. The last term on the RHS represents particle removal by a portable air cleaner, i.e. the focus of this study. Note that Equation 1 must be applied to each particle size in the indoor environment, as several of the parameters are dependent on particle size.

It is important to recognize the simplifying assumptions associated with Equation 1. These include the treatment of the indoor environment as a well-mixed reactor, treatment of all removal in the HVAC system via filtration only (no model representation of removal via deposition to components of the HVAC system such as cooling coils, fan blades, and duct walls), and no consideration of particle interaction with one another, i.e. coagulation effects that tend to shift particle size distributions. Further, for this screening assessment we did not consider any indoor sources of particles, including resuspension.

By dividing through by volume and factoring all terms that include indoor concentration allows Equation 1 to be re-written as Equation 2.

$$\frac{dC}{dt} = p\lambda C_o - \alpha C \quad (2)$$

$$\alpha = \lambda + \eta_f \frac{Q_f}{V} + v_d \frac{A}{V} + \eta_{pf} \frac{Q_{pf}}{V}$$

Separation and integration of Equation 2 with the simplifying assumption of a constant outdoor particle concentration leads to a time-dependent solution for indoor particle concentration as described by Equation 3.

$$\frac{C(t)}{C_o} = \frac{p\lambda}{\alpha} (1 - e^{-\alpha t}) \quad (3)$$

As time becomes large (usually assumed as $t > 3/\alpha$) Equation 3 approaches the steady-state solution for time equaling infinity as described by Equation 4.

$$\frac{C(\infty)}{C_o} = \frac{p\lambda}{\alpha} = \frac{p\lambda}{\lambda + \eta_f \frac{Q_f}{V} + v_d \frac{A}{V} + \eta_{pf} \frac{Q_{pf}}{V}} \quad (4)$$

This solution is clearly inappropriate for a dynamic plume of particles associated with the release of a BWA, e.g., for which C_o would likely vary considerably with time. However, it is appropriate for comparing the *relative* effectiveness of portable air cleaners to other particle removal mechanisms in a home.

For purposes of comparing the relative effectiveness of portable air cleaners as a SIP tool, we consider a parameter Γ (Equation 5), which equals the indoor particle concentration in the presence of one or more air cleaners, divided by the concentration in the same home with no air cleaner.

$$\Gamma = \frac{C(\infty)_{pf}}{C(\infty)_{nopf}} = \frac{\lambda + \eta_f \frac{Q_f}{V} + v_d \frac{A}{V}}{\lambda + \eta_f \frac{Q_f}{V} + v_d \frac{A}{V} + \eta_{pf} \frac{Q_{pf}}{V}} \quad (5)$$

The parameter Γ was used to determine the relative effectiveness of portable air cleaners for various particle sizes relative to scenarios in which such air cleaners are not employed. As is depicted in Equation 5, the relative effectiveness of portable air cleaners as a SIP tool depends not only on parameters that define the air cleaner itself, but also the magnitude of air exchange rate, removal by filtration in an HVAC system, and particle deposition. All terms but the air exchange rate in Equation 5 depend on particle diameter and, as such, the relative effectiveness (Γ) of portable air cleaners as a SIP tool should also depend on particle size. For a given particle size, Γ approaches unity for a completely ineffective air cleaner and zero for an ideal air cleaner.

Equations 4 and 5 comprise the screening model and metric, respectively, used for this assessment of portable air cleaners as possible tools to be employed for residential SIP strategies. Key parameters that were used in the assessment are described in the following sub-section.

Model parameters

In order to determine the model parameters for Equations 4 and 5, we used experimental data from our previous work (Ward et al., 2003) to determine $\eta_{pf} Q_{pf}$ and values from the literature to determine all of the other parameters. We are interested in a particle size range from 0.1 to 2 μm , which is the range of interest for many BWAs. These particles are also likely to be the most persistent in indoor environments because they have very long characteristic removal times by gravitational settling, and they

are too large to be substantially removed by Brownian diffusion.

The volume of a typical home was selected by considering the typical home area from the 2001 US Bureau of the Census (2001) of 157 m² and multiplying it by an assumed ceiling height of 2.4 m, for a volume of 377 m³.

Based on the work of Liu and Nazaroff (2001, 2003), the penetration factor (p) was assumed to be unity for all particle sizes of interest. Note that particle penetration across the building envelope varies and can be less than unity, particularly for particles larger than 1 μm . We use p equal to unity as a plausible screening estimate.

The air exchange rate (λ) was determined from a study of 2844 American homes by Murray and Burmaster (1995). We chose the median value of 0.5/h for our base case and also considered the 10 and 90% values of 0.2/h and 1.3/h for bounds on this parameter.

The term $v_d A/V$ is often referred to as the deposition loss rate. We adopted size-dependent deposition loss rates as summarized by Riley et al. (2002), based on their review of the published literature. The values that we used for $v_d A/V$ are listed in Table 1.

The HVAC filter efficiency (η_f) was determined for a typical residential furnace filter from experiments by Hanley et al. (1994). We also considered the case of a new high-performance filter (Hanley et al., 1999). Table 1 lists the values we used for η_f .

The flow through the air handler (Q_f) was determined by assuming a 3.5-ton air conditioner and considering measured results to determine the recommended HVAC flow of 2040 m³/h. For simplicity we have not included duct leakage. We considered two cases of HVAC control: in the first case the HVAC blower runs continuously (performed for mechanical ventilation), in the second case the blower cycles on and off and runs for an average of 10 min every hour.

For purposes of comparison, we defined a base case combination of the four varied parameters:

- Air exchange rate, $\lambda = 0.5/\text{h}$.
- HVAC filter efficiency, η_f as a function of particle diameter from standard, i.e. low-efficiency, furnace filter from Hanley et al. (1994).
- HVAC flow rate, $Q_f = 340 \text{ m}^3/\text{h}$, i.e. cycling 10 min every hour.
- Single portable air cleaner with average CADR, defined as the product of η_{pf} and Q_{pf} , as a function of particle size from chamber experiments (Ward et al., 2003).

To obtain size-resolved CADRs for common residential air cleaners, tests were conducted in an 11 m³ stainless steel chamber in which one of three portable HEPA air cleaners was operated against a polydisperse aerosol generated by burning incense. By comparing particle number concentration decay with the air cleaner switched off to the decay with the air cleaner switched on, CADRs were calculated for each of three air cleaners for seven particle size categories. We used the average values for each particle size range, as listed in Table 1.

Results

Every combination of the two HVAC filter efficiencies, three HVAC flow rates, and three air exchange rates was modeled for cases in which zero, one, two, and three air cleaners were activated. Relative air cleaner effectiveness (Γ) and normalized indoor concentration (C/C_o) were plotted as functions of particle diameter for each case. Fifteen cases of particular interest were selected for presentation and are shown in Figures 1–4. Each graph presents a group of related cases for comparison. The base case has been included in each graph to serve as a reference. Values of Γ and C/C_o should be interpreted as in the following examples: $\Gamma = 0.3$ means that the steady-state indoor concentration is 30% of what it would be if no air cleaner was activated; $C/C_o = 0.4$ means that the steady-state indoor concentration is 40% of the outdoor concentration.

Figure 1a shows the boundary envelope for Γ . The curve labeled ‘lowest Γ with three air cleaners’ represents the case where the air cleaner contribution to particle removal relative to other removal mechanisms is maximized. This case occurs when the air exchange rate is low and the HVAC system is not running. The upper limit of Γ corresponds to the case where no air cleaner is operating. As the upper limit of Γ equals unity, we have substituted the curve labeled ‘highest Γ with one air cleaner’ to represent the upper meaningful bound of Γ . To summarize Figure 1a, the lowest concentration possible with three air cleaners activated is about 10% of what it would be with no air cleaners, and the concentration with one air cleaner activated varies between about 25 and 80% of what it would be with

Table 1. Particle size dependent parameter values

Particle diameter (μm)	Deposition loss coefficient ^a , $v_d A/V$ (per hour)	HVAC filter particle removal efficiency ^b , η_f		CADR ^c , $\eta_{\text{pf}} Q_{\text{pf}}$ (m ³ /h)	
		High	Base	Average	s.d.
0.1–0.2	0.0396	0.28	0.03	271	44
0.2–0.3	0.0432	0.29	0.04	307	44
0.3–0.4	0.0612	0.31	0.05	313	46
0.4–0.5	0.0792	0.35	0.06	318	48
0.5–0.7	0.1080	0.42	0.08	325	50
0.7–1.0	0.1800	0.52	0.10	332	54
1.0–2.0	0.3600	0.65	0.20	332	52

^aRiley et al., 2002.

^bHanley et al., 1994, 1999.

^cWard et al., 2003.

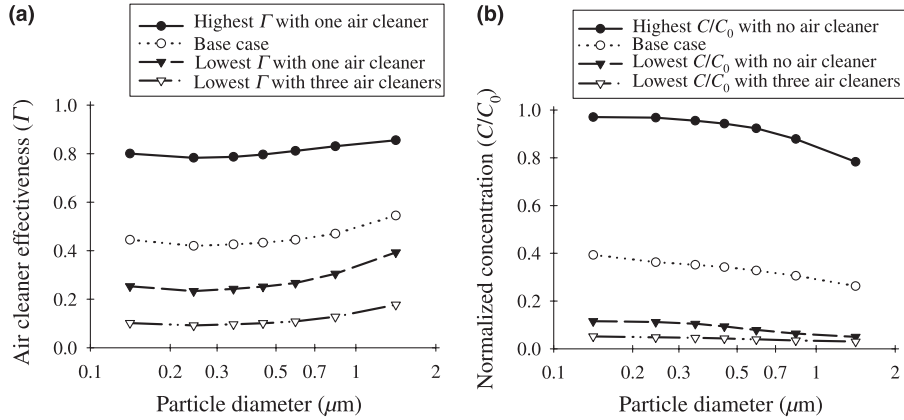


Fig. 1 Upper and lower bounds on (a) air cleaner effectiveness (lower Γ is more effective) and (b) indoor concentration normalized by outdoor concentration for different numbers of air cleaners

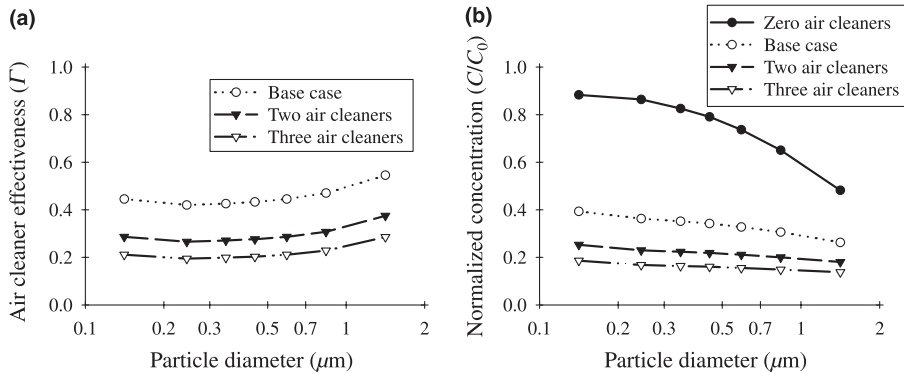


Fig. 2 (a) Air cleaner effectiveness (lower Γ is more effective) and (b) indoor concentration normalized by outdoor concentration for different numbers of air cleaners

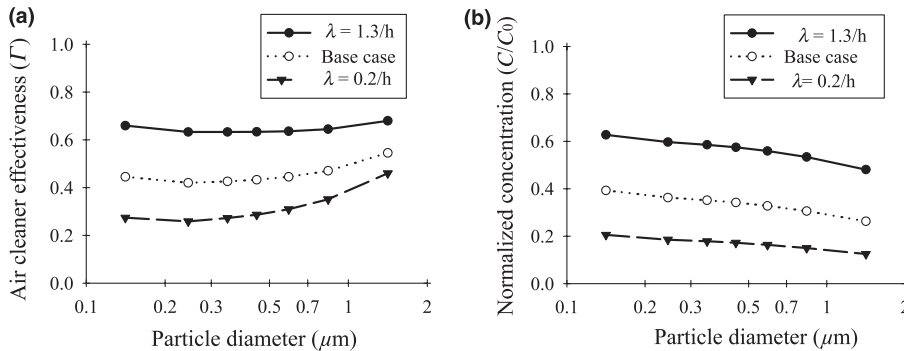


Fig. 3 (a) Air cleaner effectiveness (lower Γ is more effective) and (b) indoor concentration normalized by outdoor concentration for different air exchange rates (λ)

no air cleaner. Also of note is the decreasing relative air cleaner effectiveness (increasing Γ) as particle diameter increases. This trend indicates that air cleaner contributions to particle removal drop for larger particles for which interior surface deposition and removal by filtration in the HVAC system both increase.

Figure 1b shows the relative indoor concentration envelope. The upper bound curve represents the worst-

case scenario for a terrorist attack in which the HVAC system is switched off in a house with a high air exchange rate and no air cleaner. In this case the indoor concentration is almost the same as the outdoor concentration. The lower bound represents the best case where The HVAC system runs continuously with a high-performance filter in a house with a low air exchange rate and three portable air cleaners in

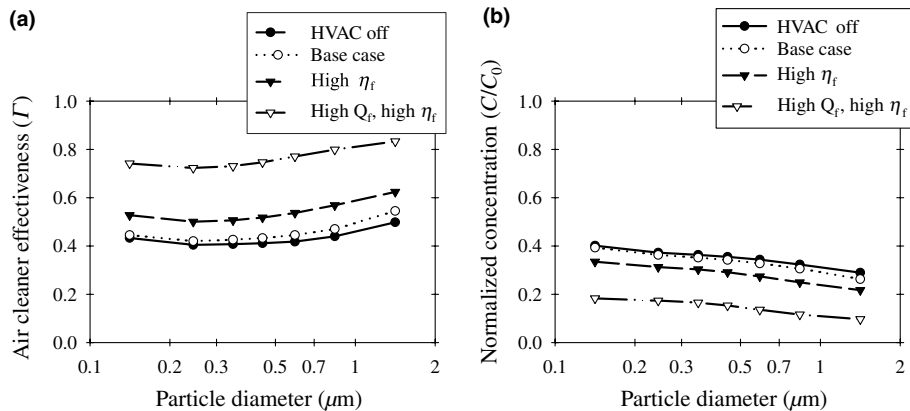


Fig. 4 (a) Air cleaner effectiveness (lower Γ is more effective) and (b) indoor concentration normalized by outdoor concentration for different HVAC flow rates (Q_f) and HVAC filter efficiencies (η_f)

operation. Under these circumstances the indoor concentration can be kept below 10% of the outdoor concentration. Of note is that when the particle removal contribution of all parameters is maximized, there is little difference between the cases where none and three air cleaners are activated. This indicates diminishing returns as the relative indoor concentration approaches zero. However, the small difference in the lower curves in Figure 1b still represents a 50% decrease in relative indoor particle number concentration.

Each curve in Figure 2–4 differs from the base case as indicated by its legend label. This method of presentation visually isolates the effect of individual variables. Figure 2a,b show the base case modified by changing the number of air cleaners, Figure 3a,b show the base case modified by varying the air exchange rate, and Figure 4a,b show the base case modified by varying the HVAC parameters.

Figure 2a,b indicate a moderate effect from increasing the number of air cleaners from one to three. However, the effect of increasing the number of air cleaners from zero to one is substantial, especially for smaller particles. Figure 2b shows the diminishing returns of adding more air cleaners.

The curves in Figure 3a indicate a significant relative air cleaner effectiveness when the air exchange rate is low and a diminished but still substantial relative effectiveness when the air exchange rate is high. The results presented in Figure 3 demonstrate the tendency of outside air exchange to overwhelm the contribution to particle removal of air cleaners. The difference in Γ between low and high λ is very much dependent on particle size, but the difference in C/C_0 between low and high λ is not. This observation can be explained by the fact that air cleaners have their greatest effect relative to other factors on particles around 0.25 μm and decrease in relative effectiveness as particle size increases. That trend does not appear in Figure 3b because C/C_0 does not indicate the effectiveness of air cleaners relative to other variables.

Figure 4 shows curves representing maximum and minimum HVAC contributions to particle removal. High-performance filtration and continuous flow are combined to yield the maximum HVAC removal curves. Curves showing the base case with a high efficiency filter are included to show the relative contribution of filter efficiency to HVAC removal. Both graphs indicate the importance of HVAC filter efficiency. The similarity between the cases when the HVAC system is on and off can be explained by the fact that the base case HVAC filter efficiency is quite low (typical of residential furnace filters), which allows little HVAC removal even for continuous flow. It is important to recognize that this model considers only the contribution of the HVAC filter. A more rigorous treatment of the HVAC system would include parameters for deposition on other HVAC components.

To assess the generality of our results to non-steady-state conditions, we have considered a simplified transient BWA release scenario: the outdoor concentration of particles (assumed monodisperse with an aerodynamic diameter of 0.6 μm for simplicity) increases instantaneously from zero to an arbitrary constant level, persists for 1 h, and then drops instantaneously to zero. All other conditions are as described above for the steady-state analysis.

The transient indoor response to the outdoor release scenario described above is shown by plotting Equation 3, as shown in Figure 5. Figure 5 shows the indoor concentrations for the base case (normalized by the magnitude of outdoor concentration during the release), with and without an air cleaner, plotted as a function of time starting at the beginning of the 1-h particle release. During the period of high outdoor concentration ($0 < t < 1$ h) a single stand-alone air cleaner reduces the indoor concentration, and after the outdoor plume passes an air cleaner causes the indoor concentration to drop faster than with no air cleaner.

To avoid problems associated with application of Equation 3 to solve for Γ for a time variant outdoor

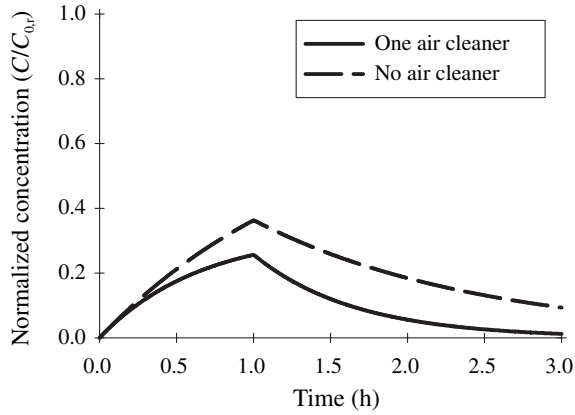


Fig. 5 Indoor concentration during and after an outdoor biological warfare release. At 1 h the outdoor concentration drops to zero, and C/C_o would be undefined. Therefore, $C/C_{0,r} = C(t)/C_o$ ($0 < t < 1$ h)

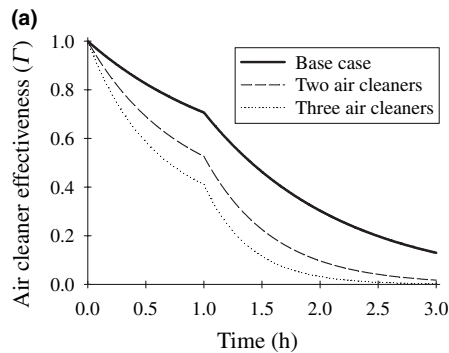
concentration, we solved Equation 2 numerically as shown in Equations 6 and 7. $\Gamma(t)$ can be calculated as shown in Equation 8.

$$\frac{C^{n+1} - C^n}{\Delta t} = p\lambda \frac{C_o^n + C_o^{n+1}}{2} - \alpha \frac{C^n + C^{n+1}}{2} \quad (6)$$

$$C^{n+1} = \frac{\frac{p\lambda\Delta t}{2}(C_o^n + C_o^{n+1}) + C^n(1 - \frac{\alpha\Delta t}{2})}{1 + \frac{\alpha\Delta t}{2}} \quad (7)$$

$$\begin{aligned} \Gamma^{n+1} &= \frac{C_{\text{pf}}^{n+1}}{C_{\text{nopf}}^{n+1}} \\ &= \frac{\left\{ \frac{p\lambda\Delta t}{2}(C_o^n + C_o^{n+1}) + C^n(1 - \frac{\alpha\Delta t}{2}) \right\}_{\text{pf}} \left\{ 1 + \frac{\alpha\Delta t}{2} \right\}_{\text{nopf}}}{\left\{ \frac{p\lambda\Delta t}{2}(C_o^n + C_o^{n+1}) + C^n(1 - \frac{\alpha\Delta t}{2}) \right\}_{\text{nopf}} \left\{ 1 + \frac{\alpha\Delta t}{2} \right\}_{\text{pf}}} \quad (8) \end{aligned}$$

Figure 6a, the transient analog to Figure 2a, shows $\Gamma(t)$ for the base case, base case with two air cleaners,



and base case with three air cleaners. Figure 6b, the transient analog to Figure 3a, shows $\Gamma(t)$ for the base case, low λ , and high λ .

Figure 6 corroborates the steady-state results. The indoor concentration is significantly reduced compared with what it would be with no air cleaner. Also, the relative effectiveness of air cleaners increases with time both during the period of high outdoor concentration and afterward. However, the reason $\Gamma(t=0)$ equals unity (as opposed to zero or some other value) is less obvious as C_{pf} and C_{nopf} both equal zero at time zero. This issue can be clarified by applying L'Hopital's rule. The fact that Γ equals zero after a long time can be explained by the same reasoning.

Figure 6b shows an interesting result that differs from the steady-state scenario. Whereas in the steady-state scenario, the air exchange rate significantly influences the relative effectiveness of air cleaners, in the transient scenario the air exchange rate has little effect on the relative effectiveness of air cleaners. However, this result is dependent on the duration of the outdoor release. For a release lasting 1 day (highly unlikely), for example, the influence of λ on $\Gamma(t)$ would increase and approach that of the steady-state condition. This result suggests that different SIP strategies are appropriate for different attack scenarios. For example, the effectiveness of sealing cracks will increase over time as long as the concentration outdoors is higher than indoors.

Conclusions

Several useful conclusions can be drawn from this screening study. Portable air cleaners with HEPA filters can be effective for reducing indoor concentrations of particles in the size range of 0.1–2 μm , and therefore may serve as important SIP tools. Steady-state concentration reductions of approximately 50% with a single air cleaner and more than 90% for three or more air cleaners are possible in residential dwellings. The relative effectiveness of portable air cleaners with respect to reducing indoor particle counts is a weak

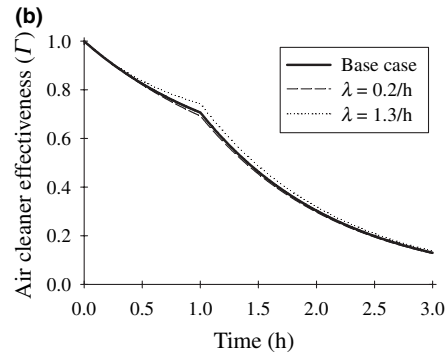


Fig. 6 Air cleaner effectiveness (lower Γ is more effective) for the transient scenario with (a) number of air cleaners and (b) air exchange rate (λ) varied

function of particle diameter, and decreases as diameter increases above $0.25\ \mu\text{m}$. High air exchange rates diminish the relative effectiveness of portable air cleaners for reducing fine particle concentrations unless the duration of high outdoor concentration is short compared with $1/\lambda$, in which case the air exchange rate has little effect on the relative air cleaner effectiveness. High HVAC contributions to fine particle removal reduce the relative effectiveness of portable air cleaners. Relative air cleaner effectiveness increases with time following an outdoor release and approaches the steady-state relative effectiveness as long as the outdoor concentration remains high. After the outdoor concentration drops below the indoor concentration, over time, air cleaners approach perfect relative effectiveness.

The authors acknowledge that the results described herein are of a screening nature, and that additional

work is needed to present a more realistic representation of certain model parameters and particle release scenarios. Specifically, indoor particle sources such as resuspension are not considered in this paper. Additionally, experimental verification of SIP techniques could provide data to validate the model presented herein. Finally, the authors hope that the work presented in this paper will facilitate future studies related to the important topic of SIP strategies.

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