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Accounting for in-situ air cleaner utilization and performance to improve interpretation of patient outcomes in real-world indoor air cleaner intervention trials

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Running Head: Indoor air cleaner clinical trials require in-situ performance measurements

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List of abbreviations

AHAM: Association of Home Appliance Manufacturers
ANSI: American National Standards Institute
CADR: clean air delivery rate
CADR/V: clean air delivery rate divided by space volume
CFM: cubic feet per minute
COPD: chronic obstructive pulmonary disease
CO_2: carbon dioxide
dBA: A-weighted decibel
ESI: Electronic Supplementary Information
HEPA: high-efficiency particulate air
HUD: Housing and Urban Development
IRB: Institutional Review Board
IT: information technology
JBVAMC: Jesse Brown Veterans Affairs Medical Center
NIOSH: National Institute for Occupational Safety and Health
NO_2: nitrogen dioxide
O_3: ozone
PM: particulate matter
SGRQ: St. George's Respiratory Questionnaire
UVGI: ultraviolet germicidal irradiation
VOC: volatile organic compounds

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Abstract

There is an increasing number of randomized clinical trials intended to assess the effectiveness of indoor air cleaners for improving participant outcomes in real-world settings. In this communication, we synthesize the current state of registered air cleaner intervention trials and call attention to the critical importance of conducting measurements to characterize the performance and in-situ utilization of air cleaners in such trials to improve interpretation of exposure measurements and patient outcomes. We draw upon the existing literature and preliminary findings from our ongoing one-year, randomized, single-blind trial of stand-alone air filtration in the homes of U.S. military Veterans to inform our recommendations. We demonstrate how to conduct industry-standard performance testing and how to use long-term measurements of air cleaner power draw to assess air cleaner operation. In our analysis of interim data from 53 homes to date with mean data collection of 275 days, we found that most air cleaners, whether active or sham, were operated predominantly at low or medium fan speeds, and most participants operated their air cleaner on predominantly one fan speed. In few homes, air cleaners were mostly off. We estimate that air cleaner operation in these homes is providing a median additional equivalent particle loss rate of ~0.7/h (ranging ~0-2.8/h). Accordingly, we recommend that real-world air cleaner intervention trials adopt the steps described herein to account for the amount of clean air delivered in real-world settings and to provide important context alongside indoor exposure measurements and analysis of patient outcomes.

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Introduction

A growing number of randomized clinical trials have shown that indoor air cleaning, especially stand-alone or in-room air filtration with high-efficiency particulate air (HEPA) filters, can reduce indoor pollutant concentrations (especially particulate matter, or PM) and provide some improvements in health outcomes or markers of outcomes for a variety of populations [1–4]. Since 2020, at least five systematic reviews of clinical intervention trials intended to evaluate the health effects (or markers of effects) of indoor air cleaning or filtration have been published, with foci on cardiovascular health [5], biomarkers of cardiorespiratory [6] or cardiovascular health [7], and blood pressure [8,9]. Moreover, there are at least 27 currently active trials registered on ClinicalTrials.gov focused on indoor air cleaning interventions, meaning they are either ongoing, recruiting, or in preparation for recruitment. While more details are provided in an overview in the electronic supporting information (ESI), most of the published randomized indoor air cleaning intervention trials to date have ranged from approximately 20 to 200 participants, which would place them generally in the range of sample sizes that are typical for Phase I/II clinical trials [10], with durations of interventions ranging from half a day to as long as one year (medians of ~7-14 days). They also typically, but not always, include at least one type of indoor exposure measurement, which is necessarily limited in scope and/or duration by practical factors such as time, technology, funding, or other resources to support indoor environmental sampling and analysis. Indoor exposures are also influenced by a range of factors in addition to air cleaner status (e.g., sham/placebo versus true), including pollutant source strength, building characteristics (e.g., air infiltration, airflow through window and door openings), and other competing pollutant removal mechanisms (e.g., central air filtration, deposition to surfaces).

Within this context, there remains one important limitation to many of the past, ongoing, and planned intervention trials: their level of detail in characterizing in-situ air cleaner utilization and performance has varied widely. Such performance metrics and measurements are crucial for contextualizing and interpreting outcomes in air cleaning intervention trials. Otherwise, differences in in-situ air cleaner performance and/or

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adherence (i.e., usage), if unaccounted for, can lead to misinterpretations or even erroneous conclusions from an intervention study.

To illustrate, in a recent review of interventions for respiratory outcomes (including indoor air cleaning) published in the prior 3 years, Robertson et al. (2024) [11] observed that while all 9 air cleaner intervention studies that were implemented within the general population reported measurements of the average efficacy of air cleaner interventions on at least one target pollutant (i.e., the resulting impact on indoor pollutant concentrations), "few provided details on the clean air delivery rate of the air cleaners," "few studies reported intervention adherence," and "uniform definitions for adherence were not used."

Even among the three reviewed studies that included "objective measurements of air cleaner adherence at high temporal resolution," their approaches were inconsistent and did not yield a full picture of in-situ operation or performance. One of those studies [12] utilized custom air cleaners that were "equipped with a counter that recorded the number of hours the machine was plugged into a power source", which is not the same as logging usage or amount of clean air output. This study did include initial and final measurements of air cleaner airflow rates but did not characterize the clean air delivery rate (CADR) for the targeted pollutants. Another of those studies [13] did not report the CADR or airflow rate of the air cleaner (and it appears the manufacturer also does not report the CADR for the device), but did use motor on/off data loggers to record air cleaner on/off status, which provides some insight into air cleaner usage. However, on/off measurements do not allow for distinguishing in-situ fan speed operation, which also affects the amount of clean air that is supplied. Further, without knowing the CADR, one cannot ascertain the amount of clean air delivery that is possible.[1] Ultimately, findings regarding primary patient outcomes were inconclusive in both studies, which may have been due in part to real effects but may also have been due in part to differences in air cleaner performance or utilization that were not fully characterized. Relying solely on indoor concentration measurements to characterize

[1] A longer introduction to CADR and industry-standard approaches to air cleaner testing is provided in the electronic supplemental information (ESI) as a reference.

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exposures without concurrent measurements of in-situ air cleaner utilization or performance limits the extent to which any observed differences in indoor concentrations, for example between sham and control groups, can be plausibly attributed to air cleaner operation.

Conversely, Hansel et al. [14] reported on an air cleaner intervention trial with nearly 100 individuals with COPD who received either active HEPA (and carbon) or sham air cleaners and completed a 6-month follow-up. While the CADR was not reported (and the manufacturer also does not report it), current transducers were used to record how often the air cleaners were utilized in participant homes. Analyzing the primary outcome data (St. George's Respiratory Questionnaire, or SGRQ, scores) across all subjects, there were no significant differences in SGRQ scores between true and sham filter groups. However, analyzing data from those individuals that utilized the air cleaner more than 80% of the time, there was a statistically significant difference in SGRQ scores between the true filter group compared to the sham filter.

It is perhaps an all-to-obvious point to make to those familiar with indoor environments and systems, but it is a point that has been often overlooked in many prior studies: it is critical to assess the in-situ utilization and performance of air cleaning interventions in indoor air cleaning intervention trials. If studies fail to account for in-situ air cleaner utilization and performance, then conclusions drawn regarding health outcomes may lack sufficient context for full interpretation. In this communication, we provide recommendations for indoor air cleaning trials to incorporate approaches to conducting in-situ measurements of air cleaner performance and analyzing performance data to help improve interpretation of trial outcomes. We draw upon the existing literature and preliminary findings from our ongoing, real-world, one-year, randomized, single-blind, controlled clinical trial of stand-alone indoor HEPA filtration in the homes of U.S. military Veterans with moderate-to-severe COPD in and around Chicago, Illinois USA to inform our recommendations. The study was approved by the Institutional Review Board (IRB) at both the Illinois Institute of Technology (#2022-92) and Jesse Brown VA Medical Center (#1675992). The trial is registered at ClinicalTrials.gov (NCT05913765) [15]. Details of study protocol are provided elsewhere [16]. The trial is still going.

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Methods

Measuring air cleaner performance

Fan-powered air cleaning devices are most commonly rated for their CADR [17] for particles, but seldom for gases like volatile organic compounds (VOCs) or nitrogen dioxide (NO_2). The CADR is most commonly reported only on the highest fan speed setting, which also tends to be the loudest setting [18]. In our experience, a minority of air cleaner manufacturers report CADR on lower fan speed settings. Therefore, to understand air cleaner performance in intervention trials, we recommend first conducting independent laboratory evaluations of CADR at a range of possible fan speed settings for pollutant(s) of concern. For readers who are less familiar, in the ESI we provide a demonstration of how to conduct an independent laboratory evaluation of the CADR of a portable air cleaner for multiple pollutants, as well as other performance characteristics such as noise levels, following a combination of industry-standard and custom air cleaner performance testing approaches.

Second, we recommend that intervention trials measure in-situ air cleaner utilization, not only via binary on/off measurements, but also with high resolution time resolved power draw (or current draw) measurements to characterize fan speed settings in addition to on, off, or unplugged status [19–23]. Doing so can allow for greater interpretation of any collected patient outcome data within the context of the amount of clean air delivered and thus the magnitude of reductions in pollutant exposure that would be expected to be achieved. When paired alongside indoor concentration measurements, such data can offer greater insight into the true impacts of the air cleaner.

Measuring air cleaner utilization in an ongoing air cleaner trial

In our ongoing indoor air cleaner intervention trial, half the participants are randomized to receive a placebo/sham filtration unit (i.e., an air cleaner with the filter removed and replaced with custom-made weights to mimic the weight of a normal unit) and half are randomized to receive a normally functioning HEPA filtration unit. During the initial air cleaner deployment visit to participant homes, the air cleaner is installed by the research team in a convenient location, ideally near where participants report spending most of their time (usually a living room or bedroom) but also informed by availability of space and access to an electrical power outlet. Outlet extensions or power strips are given to participants to avoid occupying available outlets, which are often limited. During this deployment visit, the research team first briefly measures noise from the air cleaners as installed in the field using the NIOSH Sound Level Meter app [24] on a smartphone. The participants are informed that the units clean the most air at the higher fan speed settings. However, we observed during the on-site visits that most participants initially preferred low or medium fan speed settings due to the high noise level for the high fan speed setting.

Each air cleaner (whether true/active or sham/placebo) is then plugged into an Onset UX120 HOBO Plug Load Data Logger [25] to monitor their operational runtime at high time resolution (i.e., 5-minute intervals, launched using the “at interval” function in HOBOware to yield consistent time stamps at :00 seconds) throughout the 1-year study duration. The logger measures voltage, amperage, and power draw, which allows for the team to ascertain not only when an air cleaner unit is in operation (i.e., >0 W) but whether it is operating on low, medium, or high fan speed settings. The separate current and voltage measurement also allows for understanding if, and when, the air cleaner is unplugged (i.e., 0 V and 0 A).

Spot measurements of power draw are also manually recorded on low, medium, and high fan speed settings at the initial deployment visit as well as any interim and final visits to record how power draw may have changed at each setting over time as the filter becomes loaded with collected particles/dust. Other approaches to monitor in-situ air cleaner operation could utilize data logging anemometers [26,27], motor on/off loggers [13], or smart plug devices [28], each of which can be used both for portable or in-room air cleaners as well as in-duct devices in central forced air heating or cooling systems. Each runtime measurement approach also has strengths and weaknesses. A strength of the plug load data logger approach is that it is highly accurate and allows for detecting unplugged conditions as well as fan speed settings, but weaknesses are cost (currently ~$300 USD each), lack of remote monitoring capability, and lack of utility for

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monitoring the runtime of central air handler fans. Most data logging anemometers similarly provide high fan speed setting resolution, similar cost, and no remote monitoring, with an added challenge of needing a somewhat precarious installation to mount at the air supply outlet (but they can be used for both portable and in-duct systems). Motor on/off loggers are less expensive but do not provide fan speed setting resolution and are thus less useful. Smart plug based loggers are promising but typically require either on-site Bluetooth connections to phones or custom data solutions for longer-term data logging (e.g., Raspberry Pi gateway), which are also subject to information technology (IT) security breaches [29]. Researchers should keep a watchful eye on emerging technical solutions in this arena, as there are likely emerging smart plug-based solutions that could reduce total cost of data collection while providing remote data access [30].

At some point during our yearlong study, an interim visit is conducted to each home to download data, check equipment, and conduct a housing condition assessment walkthrough, which provides a number of basic housing characteristics including floor area and home volume (among others). A final visit is conducted at least 12 months after initial deployment to retrieve data loggers. Here we use interim data from plug load loggers and housing condition assessments collected in 53 homes participating in our ongoing air cleaner intervention trial to demonstrate approaches to analysis of air cleaner utilization that can be used in other active trials. These interim data are not final, as the duration of interim data ranges from as little as 11 days to as long as 500 days, with a mean (SD) of 275 (157) days depending on when participants were recruited and when interim (or in some cases to date, final) visits were conducted. As such, these data should be considered preliminary and specific to this population; operation in other settings and in other populations may vary. Yet, such data are useful for illustrative purposes.

Merging air cleaner performance and utilization data

Once in-situ patterns of fan speed settings are characterized, a few analysis options are apparent. First, since the CADR for a given constituent can be known from prior laboratory testing (either via independent testing by the research team or provided

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by the manufacturer), any time-resolved in-home pollutant concentration or exposure data can be time-stamp-matched with the concurrent air cleaner runtime status to provide more granular analysis of the air cleaner's impact. Second, a time-averaged CADR can be calculated for any measurement duration of interest to classify the magnitude of impact that the installed air cleaner is likely delivering. For example, Equation 1 is used to calculate a time-averaged CADR for the entire duration for which data were collected in our ongoing study using preliminary runtime results.

$$CADR_{avg} = f_{low}CADR_{low} + f_{med}CADR_{med} + f_{high}CADR_{high} \quad (1)$$

Where f_{low}, f_{med}, and f_{high} are the fraction of measurement period that an air cleaner was measured to operate on low, medium, and high fan speed settings, respectively, and $CADR_{low}$, $CADR_{med}$, and $CADR_{high}$ are the CADR for a given constituent on low, medium, and high fan speed settings, respectively. This equation also accounts for times when the air cleaner was measured as off (i.e., with 0 CADR) and provides a single metric for the amount of particle-free air delivered in the home over time. For air cleaners that adjust fan speed more granularly (e.g., algorithmically based on integrated measurements of indoor pollutant concentrations), Equation 1 could be resolved more granularly or even continuously using reported or measured efficacy (e.g., CADR/W). This value can also vary over time if participants change their utilization rate over the study duration or, for some air cleaners, if the CADR on each fan speed setting changes over time (i.e., the removal efficiency and/or flow rate may change with loading, depending on the nature of loading and the contaminant(s) of concern). For the air cleaners used in our ongoing, real-world study, the CADR for all particle sizes is not expected to change significantly over the 1-year duration because the air cleaners have a large amount of HEPA filter media, although gas-phase removal efficiency may vary more widely over time. However, such characterization is beyond the scope of this work.

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Results and Discussion

Air cleaner performance testing

As summarized in the ESI (Figure S2 and Table S1), the CADR for smoke-sized particles (i.e., 0.09-1 µm) of the air cleaner used in our ongoing intervention study was measured in laboratory testing to be ~50 ft^3/min (~85 m^3/h) on low, ~80 ft^3/min (~136 m^3/h) on medium, and ~160 ft^3/min (~272 m^3/h) on high fan speed settings with the true filters installed and less than 10 cfm for all fan speeds with the sham installed. For comparison, a recent review of field studies of portable air cleaners reported that most studies used air cleaners with a CADR between 100 and 300 m^3/h (i.e., ~60 to ~175 ft^3/min), presumably measured on the highest fan speed settings [31]. The CADR for NO_2 and O_3 were both estimated to be similar to the particulate matter CADRs. Noise production on the highest fan speed setting was significantly higher than both medium and low fan speed settings (e.g., 61-62 dBA versus 46-48 dBA and 39-40 dBA, respectively).

In-situ utilization of air cleaners: interim data

Figure S3 shows an example of a few months of in-situ air cleaner power draw measurements from our ongoing study and demonstrates how the power draw data can be tagged and sorted into bins of "off", "low", "medium", and "high" fan speed operation. Figure 1 summarizes the percentage of time from the interim collected data that the air cleaners in these homes were operating on low, medium, or high fan speed settings, or were off/unplugged, sorted by active (true) and sham (placebo) air cleaner groups. Most air cleaners, whether active or sham, were operated in predominantly low or medium fan speed modes, and most participants to date have operated their air cleaner on predominantly just one fan speed setting rather than adjusting frequently. In a few homes, the air cleaners were mostly off. Further, Figure S4 summarizes the hourly mean (and standard deviation) of the air cleaner power draw measurements from the sample of 53 homes for which we have interim data to date. There were no apparent diurnal variations in mean power draw, suggesting that participants to date have rarely

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adjusted the fan speed settings throughout the day. Rather, they have generally left the fan speed setting for long periods of time, adjusting infrequently.

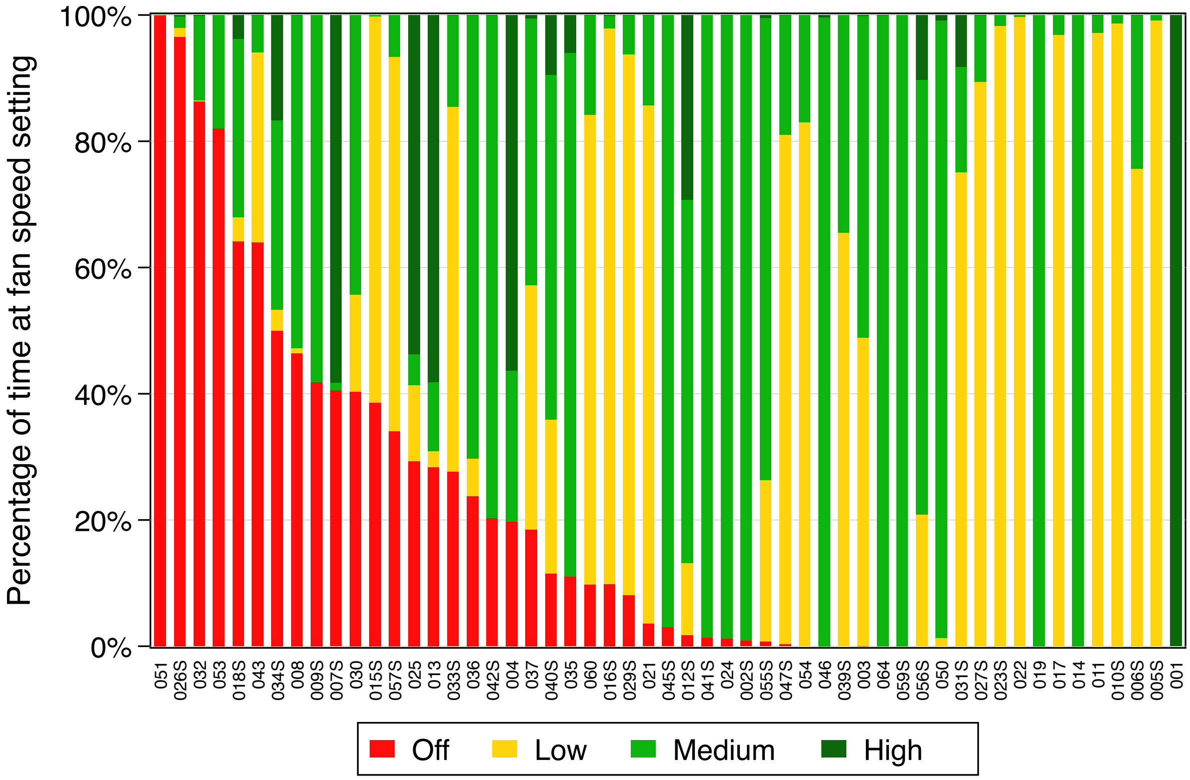

Figure 1. Summary of air cleaner operation data from 53 interim visits to date, with data ranging from approximately 2 to 10 months of operation, sorted by true and sham air cleaner groups. Homes are sorted by descending order of percentage of time the air cleaner was measured to be off. Home IDs increase incrementally with date of recruitment and randomization. Home IDs with "S" denotes a sham filter.

Figure 2a shows the distribution of time-averaged CADR for smoke-sized particles delivered in each home from these interim data collected to date, estimated by combining in-situ runtime data (from Figure 1) with lab-based measurements of CADR for smoke-sized particles (from Table S1) following Equation 1. Time-averaged CADRs for sham/placebo air cleaners are actually near 0 but are represented as what they would be if they had true filters installed because the intent is to show what their time-averaged smoke-size particle CADR would be if they were true filters. Because participants are blinded to filter status, this provides a utilization-based measure of intended effect that includes placebo.

Figure 2b shows the same time-averaged CADR values for smoke-sized particles also normalized by the measured home volume and converted to units of 1/h to be comparable to equivalent air change rates or other loss rates such as deposition to surfaces. Compared to relying solely on an exposure outcome (i.e., measured indoor pollutant concentration), which can be influenced not only by the air cleaner intervention but also local ambient conditions, building characteristics such as envelope leakage or window opening, and the presence, nature, and magnitude of indoor pollutant sources, this calculation provides a single metric for understanding how often each participant operates their air cleaner and how large of an impact that operation would be expected to have based on the relative scale of the air cleaner to the size of the home.

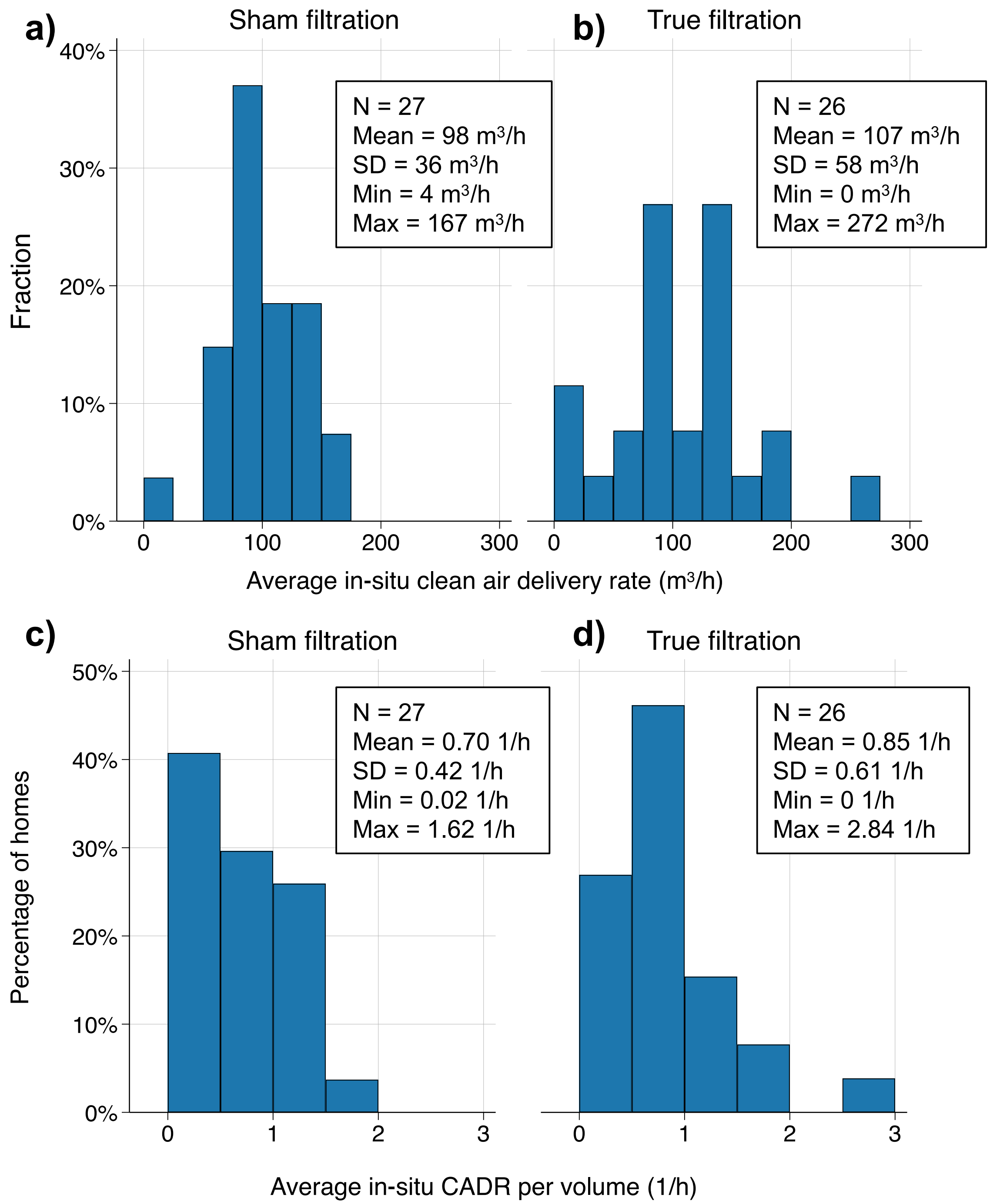

Figure 2. Interim analysis of (a & b) time-averaged in-situ CADR (m^3/h) and (c & d) CADR divided by house volume (CADR/V, 1/h) for smoke-sized particles delivered in the 53 homes with interim visits to date, split by sham and true filtration groups. Estimates of CADR

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and CADR/V for sham filtration group assume what the CADR would be if true filtration was used for direct comparison to true filtration group.

These interim data show that air cleaner operation in these homes to date (again assuming all true filtration units rather than half sham, half true) is providing anywhere between ~0 ft^3/min (~0 m^3/h) of particle-free air and ~0 per hour in equivalent particle loss rate (i.e., air cleaner is always off) to ~159 ft^3/min (~270 m^3/h) of particle-free air (i.e., air cleaner is operating on high all the time) and ~2.8 per hour in equivalent particle loss rate (i.e., air cleaner is operating on high all the time and in a relatively small volume). The mean ± SD in-situ time-averaged CADRs to date are estimated to be 60±28 ft^3/min (102±48 m^3/h) across all homes to date, 63±34 ft^3/min (107±58 m^3/h) for the true air cleaners, and 58±21 ft^3/min (99±36 m^3/h) for the sham air cleaners, with no significance between true/sham air cleaner groups to date ($p = 0.45$ from Wilcoxon-Mann-Whitney test). The mean ± SD in-situ time-averaged CADR/V values (CADR divided by house volume) are estimated to be 0.77±0.52 per hour across all homes to date, 0.85±0.61 per hour in the true air cleaner homes, and 0.70±0.42 per hour in the sham air cleaner homes, also with no significance between true and sham air cleaner groups to date ($p = 0.40$ from Wilcoxon-Mann-Whitney test).

Approximately 25% of homes are receiving less than 0.5 per hour in additional equivalent air change rate for PM, meaning that the time-averaged rate of particle removal added by the air cleaner is less than the average air change rate or natural particle deposition rate in typical U.S. homes [32,33]. In other words: the air cleaner is not doing much to improve particle removal in these homes because it is not operated often enough and/or it is inadequately sized for the space. Another ~40% of homes are receiving ~0.5-1 per hour in additional time-averaged equivalent air change rate, while only ~10% are receiving more than 1.5 per hour (ignoring sham/true status). We are not able to make direct comparisons to air change rates due to infiltration or ventilation in our study homes because they were not measured. None of our study homes to date have dedicated mechanical ventilation systems other than intermittent kitchen and/or bathroom exhaust fans, although we did observe window opening in several homes at

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our initial and/or interim visits. Future work should leverage advances in low-cost indoor air quality sensors for both particulate matter (PM) and carbon dioxide (CO_2) to assess air change rates and particle loss rates from time-resolved concentration data [34,35].

These data serve to demonstrate how air cleaner utilization and performance data are crucial for contextualizing and interpreting outcomes in real-world air cleaning intervention trials. This analysis accounts only for the CADR of a specific particle size range and assumes that CADR does not change with loading over time, which is likely true for periods of up to a few years for some HEPA filtration devices but not necessarily all [36]; the CADR for other constituents may vary at different rates. Long-term measurements of such parameters are important – and achievable with current technology – to characterize operational patterns over time and to analyze factors that influence air cleaner operation [19,21,37].

To return to the Phase I/II clinical trials analogy, such measurements would allow for controlling for the amount of clean air delivered over time in the analysis and interpretation of exposure measurements and resulting patient outcomes in air cleaner intervention trials. This approach is akin to controlling for the dosage in a clinical trial rather than assuming each participant receives the same dosage. This simple metric of clean air delivered can also be a useful surrogate for exposure (or exposure reduction) in trials that include patient outcomes but do not include indoor environmental exposure measurements (e.g., [38]). Another challenge, however, is that the dosage of clean air in this case becomes a continuous variable that can vary both between participants over the study duration and within participants over time and will need to be accounted for accordingly.

Conclusions

An increasing number of indoor air cleaner intervention trials are currently registered and in planning stages or already underway. A limited number of prior studies have demonstrated the importance of conducting in-situ air cleaner performance and utilization measurements for aiding in the interpretation of any patient outcomes, although many prior air cleaner intervention trials have not done so. As such, we aim to help inform clinical trial investigators, funding program managers, and the broader

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research community that exists at the intersection of indoor air science, exposure science, and medical intervention trials by providing recommendations for air cleaning intervention trials to incorporate approaches to conducting measurements of air cleaner performance and utilization and analyzing such data to help improve interpretation of trial outcomes. We argue that for such trials to be successful and informative regarding the efficacy of air cleaners for improving patient outcomes in real-world settings, they should leverage the approaches described herein to account for the amount of clean air delivered over time in each participant's setting. Doing so will provide important context to concurrent indoor exposure measurements and analysis of patient outcomes.

Competing Interests

The authors declare no competing interests.

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