

Use of air-cleaning devices to create airborne particle-free spaces intended to alleviate allergic rhinitis and asthma during sleep

Abstract Comprehensive quantitative experiments were performed to assess the capabilities of several air-cleaning devices to create a particle-free microenvironment as a therapy for sleeping persons affected by allergic rhinitis and asthma. Six devices were evaluated, of which five were portable and intended to provide general air cleaning for bedroom-sized spaces. The sixth was intended for installation in front of the headboard of a bed and was designed to provide clean air focused in a space occupied by a sleeping person. The air-cleaning methods of the selected devices included high-efficiency particulate air (HEPA) filtering and electrostatic precipitation. Particle concentration measurements for six particle-size ranges and sound intensity measurements were made during 8-h, sleep-simulating periods. The effects of four parameters were studied: (i) device location, (ii) controlled air motion in the laboratory, (iii) airflow rate setting of the air-cleaning device, and (iv) controlled disturbances. To ensure a totally objective study, a special laboratory facility was constructed which enabled complete control of the experimental conditions. The measured concentration histories provided comprehensive evidence of the relative capabilities of the various devices for the specific air-cleaning function. It was found that the device designed to focus the cleaned air in the sleeping space fulfilled its goal and, in that regard, was clearly superior to all of the other air-cleaning devices.

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Practical Implications

There is evidence that allergic reactions are triggered by the presence of airborne particles and that these reactions can be mitigated by particle removal. This strategy can be implemented by the use of air-cleaning devices which are capable of creating particle-free zones at locations where human activity occurs. In particular, the creation of a particle-free zone which encompasses the breathing space of a sleeping person holds promise of mitigating sleep-disturbing allergic reactions.

Introduction

It is well established that allergic rhinitis and asthma are triggered by the presence of airborne particulates. The discomfort associated with allergic rhinitis and asthma may be experienced at any time of a day; however, the impact of the discomfort is, in all likelihood, the greatest during periods when sleep is being sought (Craig et al., 2004). It has been suggested that the use of air-cleaning devices might provide mitigation for this malaise (van der Heide et al., 1997; Nelson et al., 1988). This issue is of such prominence that air-cleaning devices which purport to control particulates in sleeping environments are now widely available. In the past, the performance of commercially available air-cleaning devices has been described in terms of symptom relief (Antonicelli et al., 1991; Warburton et al., 1994; Zwemer and Karibo, 1973).

In contrast, definitive quantitative information about the particle removal capabilities of these devices in sleeping environments is not available.

A search of the relevant literature revealed only three papers in which the characteristics of several different air-cleaning devices were compared. In the first, Shaughnessy et al. (1994), no consideration was given to (i) device location, (ii) controlled air motion in the laboratory, (iii) airflow rate setting of the air-cleaning device, and (iv) controlled disturbances. Furthermore, the particulates were introduced into the test space separately and specifically for each data run. In contrast, in the present study, the foregoing parameters were systematically varied and, furthermore, the participating particulates are those that naturally occur in a bedroom-like environment. The second and third studies, respectively Fugler et al. (2000) and Offermann et al. (1992), were devoted to different types of filters

placed in air ducts used for distributing heated or cooled air in entire residences, and are not of direct relevance to the subject being considered here.

In a paper by Reisman et al. (1990), a single air-cleaning device was evaluated in 32 different bedrooms, but without control of the particulate environment at any site. In another test (Cheng et al., 1998) of a single air cleaner situated in a bedroom, gross particle concentrations were made as a function of time, but the only parameter that was varied systematically during this experiment was the rate at which the bedroom was ventilated. Still another study (Villaveces et al., 1977) of the performance of a single device made occasional use of an electronic particle counter, but the focus of the work was on symptomatic responses of human beings to the presence or absence of air cleaning.

Other studies on air-cleaning devices were encountered during the literature survey, but only those discussed in the preceding paragraphs involved quantitative measurement of particle populations. In none of the published papers that were read by the present authors were measurements made of the sound intensities produced by the air-cleaning devices.

The experimental investigation to be reported here was undertaken to obtain definitive data for the characterization of six, randomly chosen air-cleaning devices that are designed for use in restricted spaces. The specific modes of particle removal used in selected air-cleaning devices will be described later. To achieve equitable results that truly characterize the individual devices, a tightly controlled protocol, common to all devices, was employed. Among the evaluated devices, five, all portable, were intended to perform air-cleaning functions for bedroom-size spaces, while the sixth is meant primarily to provide a clear-air volume on a bed. The latter was situated at reading-lamp height in front of the headboard of the bed. In order to avoid any hint of commercialism, the selected air-cleaning devices will not be named; they are, however, shown in a photograph and assigned the designations A, B,..., F.

The methodology used for the quantitative evaluation of the air-cleaning capability of the selected devices is the measurement of particle concentration in six different size ranges as a function of time during an 8-h interval. That interval was intended to represent the typical sleep period. The use of particle concentration measurements as the basis of air-cleaning quality was made to achieve a fully objective characterization. Human symptomatic response to the different air-cleaning devices was rejected as a measure of comparison because it was regarded as subjective rather than objective.

To facilitate the experiments, a dedicated laboratory was constructed which enabled absolute control of air currents within that laboratory. It was equipped with bedroom furniture which was kept unchanged

throughout the entire duration of the study. A number of independent parameters were varied systematically. They included: (i) device location, (ii) controlled air motion in the laboratory, (iii) airflow rate settings of the air-cleaning devices, and (iv) controlled disturbances.

All of the five portable air-cleaning devices were situated at two different locations during the course of the experiments. One of these locations was on a nightstand positioned immediately adjacent to the headboard of the bed, while the other location was in the corner of the laboratory farthest from the headboard-adjacent position. With regard to controlled air motion within the laboratory, three different cases were implemented. In one of these, neither air ingress nor egress was permitted. In a second case, air was blown into the laboratory via a conventional floor vent and exhausted through a return grille such that the flow path did not pass over the bed. In contrast, in the third case, the locations of the inlet vent and the exit grille were chosen so as to cause the airflow path to pass over the bed. In cases 2 and 3, the airflow was maintained at 1.7 m³/min (60 ft³/min). This flow rate corresponds to a ventilation rate of approximately four air changes per hour in the laboratory.

For all six of the evaluated devices, both the highest and lowest of the available airflow rate settings were employed for the experiments. For the majority of the experiments, the laboratory was free of disturbances except for those created by the aforementioned blown air and by the air-cleaning devices themselves. In fact, the laboratory was sealed tight and was not entered during the duration of each 8-h data run. However, in a special set of data runs, a mechanical disturbance device was positioned on the bed in order to cause particles to become airborne. The disturbance was programmed to occur at 20-min intervals.

Another major feature of air-cleaning devices that is relevant to their applicability in confined spaces is the sound intensity produced. In the present study, the sound intensity associated with each of the six studied air-cleaning devices was recorded.

Materials and methods

The experimental facility

To ensure that the experiments could be performed under precisely controlled conditions, a dedicated experimental facility was designed and fabricated. A plan view of the test facility showing the location of various relevant features is presented in Figure 1. The facility consisted of a fully enclosed space which is, in essence, a room within a room. The experiments were performed in the inner of these rooms, while the outer room served as a buffer to isolate the internal space from any disturbances which might occur in the

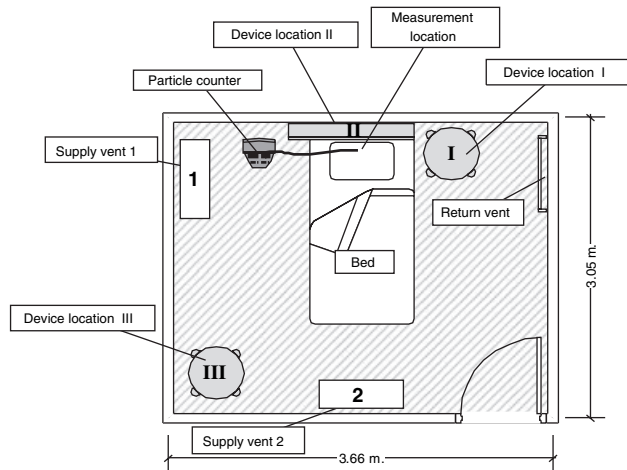


Fig. 1 Plan view of the test facility. Each key feature is depicted and labeled

building proper. Furthermore, the facility is situated in a deep basement and is located far from any external walls. It was free of ventilation and extraneous air currents, except for ventilation that was imposed as part of the test protocol.

The test site was designed to reproduce a typical bedroom in a residence with a dimension of $3.66 \times 3.05 \times 2.44$ m ($12 \times 10 \times 8$ ft). Situated within the room is a standard twin bed along with appropriate bedding, pillow, and headboard. Also present is a nightstand on which were placed the various air-cleaning devices used during the course of the experiments.

Provision was made for controlled airflow within the test chamber. To this end, several air inflow vents and several outflow vents were installed, the former in the floor of the site and the latter in the sidewalls. The inflow vents were used one at a time, and the air inflow was supplied by a dedicated blower. The initial design enabled any combination of locations of an inflow vent and an outflow vent to be used. In practice, it was found that certain combinations of vents led to a maximum effect on the air-cleaning capabilities of the tested devices, and these combinations were used for the experiments. A number of experiments were performed with both the inflow and outflow vents fully closed.

The collection of data was focused on a location that corresponded to the expected position of the head of a sleeping person. In about half of the data runs, each air-cleaning device was placed on a nightstand situated at the bedside immediately adjacent to the headboard. For the other half of the data runs, each device was positioned in the far corner of the room opposite the headboard.

A special feature of the test protocol was the use of a mechanism which periodically stirred the bedclothes at intervals of 20 min. This mechanism was used to model

the effect of possible involuntary movements of a sleeping person. Such involuntary motions tend to disturb the bedclothes which then release a shower of previously settled particulates into the air. The 20-min interval between imposed disturbances was chosen on the basis of sleep studies reported in a paper by Roehrs et al. (1996).

Data on the instantaneous sizes and concentrations of the particulates that were sampled at the sleeping site were collected by means of a laser particle counter (model CI-2300; Climet, Redlands, CA, USA). This instrument was programmed to collect a sample at 1-min intervals over an 8-h period (a normal sleep period) and to store the data until needed. The data were downloaded to a desktop computer prior to the initiation of a new data run. Each sample analyzed by the particle counter consisted of a 0.00283 m^3 (0.1 ft^3) volume of air. The particle counter categorizes the collected particulates into six size ranges: 0.3–0.5, 0.5–1, 1–5, 5–10, 10–25, and $> 25 \text{ }\mu\text{m}$.

The air-cleaning devices

The air-cleaning devices selected for study were based on either of two fundamental filtration methods. These included high-efficiency particulate air (HEPA) filtering and electrostatic precipitation. To avoid any perceived aspect of commercialism, the selected air-cleaning devices will be designated as A, B,..., and F. A photograph showing these devices is presented in Figure 2. The specific principles of operation of the individual air-cleaning devices are listed in Table 1. As can be seen from the table devices A, B, and C fall into the electrostatic precipitation category, and devices D, E, and F fall into the HEPA filtering category. All of the pictured devices are commercially available. All operate on standard 60-cycle, 110-V line power.



Fig. 2 Photograph of each device and its respective label

Table 1 Descriptions of each device and their specific operating principles

Device	Air-cleaning mechanism	Airflow direction	Other features
A	Electrostatic precipitation with a prefilter and carbon postfilter	Single horizontal direction	Portable; intended for room-size spaces
B	Electrostatic precipitation with a prefilter	Adjustable vertical direction	Portable; intended for room-size spaces
C	Electrostatic precipitation	Single horizontal direction	Portable; intended for room-size spaces
D	Electrostatic HEPA filtration with carbon postfilter	Vertical and two horizontal directions	Portable; intended for room-size spaces
E	HEPA filtration with an electrostatic prefilter	Horizontally outward and downward	Stationary; intended for focal air cleaning
F	HEPA filtration with a prefilter	Radially outward and upward	Portable; intended for room-size spaces

Experimental protocol

The efficacy of the various air-cleaning devices was investigated for a wide range of test conditions. Sixty-two individual test cases were employed during the course of the investigation. For each specified case, data were collected for both an ‘original’ run and at least a single replicate run. The test cases have been brought together and are listed in Tables 2–4.

Table 2 pertains to devices A to D and F. All of these were designed to be portable, and each was tested at

Table 2 Devices A, B, C, D, and F

Test case	Location		Vents				Airflow		Disturbance	
	I	III	No	SV1	SV2	R	Hi	Lo	No	Yes
1	X		X				X		X	
2	X		X					X	X	
3	X				X	X	X		X	
4	X				X	X		X	X	
5	X		X				X			X
6	X		X					X		X
7		X	X				X		X	
8		X	X					X	X	
9		X		X		X	X		X	
10		X		X		X		X	X	

Table 3 Device E

Test case	Location II	Vents				Airflow		Disturbance	
		No	SV1	SV2	R	Hi	Lo	No	Yes
11	X	X				X		X	
12	X	X					X	X	
13	X		X		X	X		X	
14	X		X		X		X	X	
15	X			X	X	X		X	
16	X			X	X		X	X	
17	X	X				X			X
18	X	X					X		X

Table 4 Natural settling within test site

Test case	Vents				Disturbance	
	No	SV1	SV2	R	No	Yes
19	X				X	
20		X		X	X	
21			X	X	X	
22	X					X

two locations that are respectively designated as I and III in Figure 1. Device E was not designed to be portable. Instead, it was intended to be positioned at the headboard end of a bed, with its air exit situated approximately 0.4 m above the mattress. Therefore, for the experiments involving device E, it was always positioned at location II that is indicated in Figure 1. The operating conditions for the tests involving device E are listed in Table 3, which is arranged in a manner similar to that used in Table 2.

With regard to vent-induced air movement within the test enclosure, three separate conditions were investigated. The first of these corresponds to the total absence of air inflow and outflow, and this condition is designated as *Vents – No* in Table 2. The second corresponds to inflow via supply vent 1, SV1 and outflow via the return vent R, and the third is for the combination of SV2 and R. The locations of SV1, SV2, and R are shown in Figure 1.

Each of the air-cleaning devices was equipped with the capability of moving air at different rates of flow. For each device, experiments were performed at both the highest flow setting (Hi) and at the lowest flow setting (Lo). As was mentioned earlier, a mechanism was developed to disturb the bedclothes at 20-min intervals. The presence or absence of such disturbances is indicated under the heading ‘Disturbance’ at the right end of Tables 2–4.

Prior to the implementation of any of the test conditions listed in Tables 2 and 3, data were collected on the particulate status of the ambient air within the test site in the absence of any of the air-cleaning devices. These data on the natural settling of particles served as a baseline for the characterization of the performance of the various air-cleaning devices and are listed in Table 4.

In addition to the detailed measurements of particle concentrations, the sound intensity associated with the respective air-cleaning devices was also measured. The sound-measuring instrument (Extech Model 407727, Waltham, MA, USA) had a resolution of 0.1 dBA and a threshold of 40 dBA.

Results and discussion

The presentation of results to be conveyed here is unique relative to the modes of presentation that are

more frequently encountered in the air-cleaning literature. In the literature concerned with the impact of air-cleaning devices on the moderation of particle-related allergic reactions, the presentation of the results was focused on the extent of the alleviation of the symptom in question (Antonicelli et al., 1991; Villaveces et al., 1977; Warburton et al., 1994; Zwemer and Karibo, 1973). However, the other studies on the performance of air-cleaning devices concentrated on the efficiency of the device with respect to room-scale air cleaning (Fugler et al., 2000; Offermann et al., 1992; Reisman et al., 1990; Shaughnessy et al., 1994). In contrast, the focus of the present investigation was to characterize the capabilities of various devices to create a specific particle-free volume. That particle-free volume is the space occupied by a sleeping person.

There are four major categories of results that will be reported here. The first three are concerned with the characterization of the air-cleaning capabilities of the six devices that are labeled A through F in Figure 2. This characterization is performed in terms of three indicators of particle concentration. The first of these indicators is the timewise variation of the concentration in each of six particle-size ranges measured for each of the individual air-cleaning devices and for each of the 10 operating conditions that were investigated. The second indicator used to characterize particle size concentration is a time average extended over the entire 8-h duration of a data run. The third indicator of the air-cleaning performance of the various devices is an efficiency defined by:

$$\eta = \frac{\text{particle inflow rate} - \text{particle outflow rate}}{\text{Particle inflow rate}} \quad (1)$$

or

$$\eta = 1 - \frac{\text{particle outflow rate}}{\text{particle inflow rate}} \quad (2)$$

The fourth characterization of the air-cleaning devices is the sound intensity that is attributable to each device.

The particle concentration measurements were made at the center of an envisioned microenvironment volume in which the head of a sleeping person would be situated during an 8-h sleep period. The geometry of the volume was selected with the recognition that for most sleeping persons, there may be substantial amounts of movement. The dimension of the envisioned volume is $91.44 \times 76.2 \times 45.72$ cm ($36 \times 30 \times 18$ in.), transverse width by longitudinal length measured from the headboard by height above mattress.

A very large amount of data were collected during the course of the experiments. In the forthcoming presentation of the results, these data will be organized with a view toward conveying a clear message while

presenting strong documentation that supports that message. To assist in providing clarity, the 62 test cases will be categorized into 10 separate operating conditions which are variations of the four investigated parameters.

Timewise concentration variations and time-averaged concentrations

Attention is first turned to Figure 3. This figure corresponds to one of the 10 operating conditions that were investigated. The specific conditions for Figure 3 are: (i) device location: beside the headboard (location I) for the portable devices and at the headboard (location II) for device E, (ii) neither ingress or egress of air in the laboratory space (not vented), (iii) high setting for all of the air-cleaning devices, and (iv) no imposed disturbance.

Figure 3 contains eight individual graphs. Seven of these are plots of the normalized particle concentration as a function of time for each of six particle-size ranges. Each of the size ranges is identified by a specific data symbol which is displayed in the legend that is inset at the upper-right corner of the first graph. The normalization is the ratio of the instantaneous particle concentration to the initial particle concentration for each size range. Graphs of normalized concentration vs. time are provided for each of the air-cleaning devices (A through F) and for the natural settling of the particles in the absence of any air-cleaning device. Although data were collected at 1-min intervals over the 8-h duration of a data run, the displayed data are shown at 4-min intervals in order to achieve greater clarity.

A summary of the data from the seven individual graphs is presented at the upper right via a bar graph. The bar graph displays the 8-h-average normalized concentration for each of the size ranges, for each of the individual air-cleaning devices, and for the natural settling situation. The averaging made use of the data collected at 1-min intervals.

The focus will now be directed to an interpretation of the information conveyed by Figure 3. To begin, the graph for natural settling is examined. From this, it is seen that the larger particles, > 1.0 micron, settle out rapidly and almost completely. Next, the particle removal capabilities of the various devices A through F are compared with that for natural settling. Such a comparison reveals that device C provides no improvement relative to natural settling. On the contrary, device E appears to have removed virtually all of the airborne particulates. All of the other air-cleaning devices show observable improvements relative to natural settling, but in all cases there is a substantial residual of the smaller particles (< 1 micron). Examination of the summary information provided by the bar graph at the upper right reinforces the observations and conclusions of the preceding paragraph. Clearly,

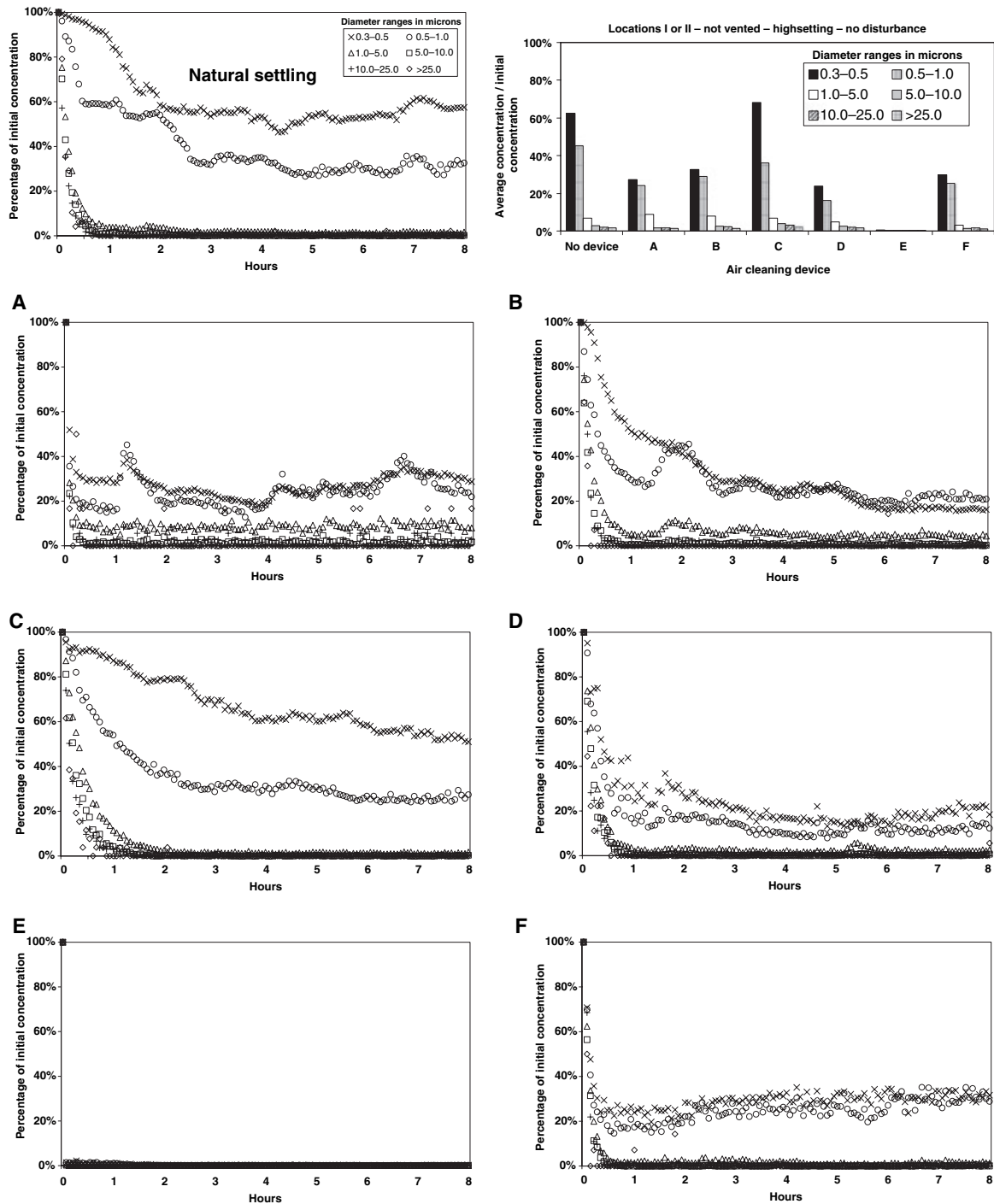


Fig. 3 Timewise concentrations and time-averaged concentrations for the specific conditions of: (i) device location: beside the headboard (location I) for the portable devices and at the headboard (location II) for device E, (ii) neither ingress or egress of air in the laboratory space (not vented), (iii) high setting for all of the air-cleaning devices, and (iv) no imposed disturbance

the conclusions about devices C and E are corroborated. It is seen that, on average, devices A, B, D, and F display nearly equal performance which lies between those of devices C and E.

Figure 4 presents the results of another operating condition in a format similar to that employed in the presentation of results in Figure 3. The operating conditions that pertain to Figure 4 are as follows: (i)

device location: location III (Figure 1) for the portable devices and at the headboard (location II) for device E, (ii) controlled airflow of four air changes per hour: supply vent 2 and return vent (Figure 1), (iii) high setting for all of the air-cleaning devices, and (iv) no imposed disturbance.

Reference is first made to the results for natural settling that are shown at the upper left of Figure 4. In

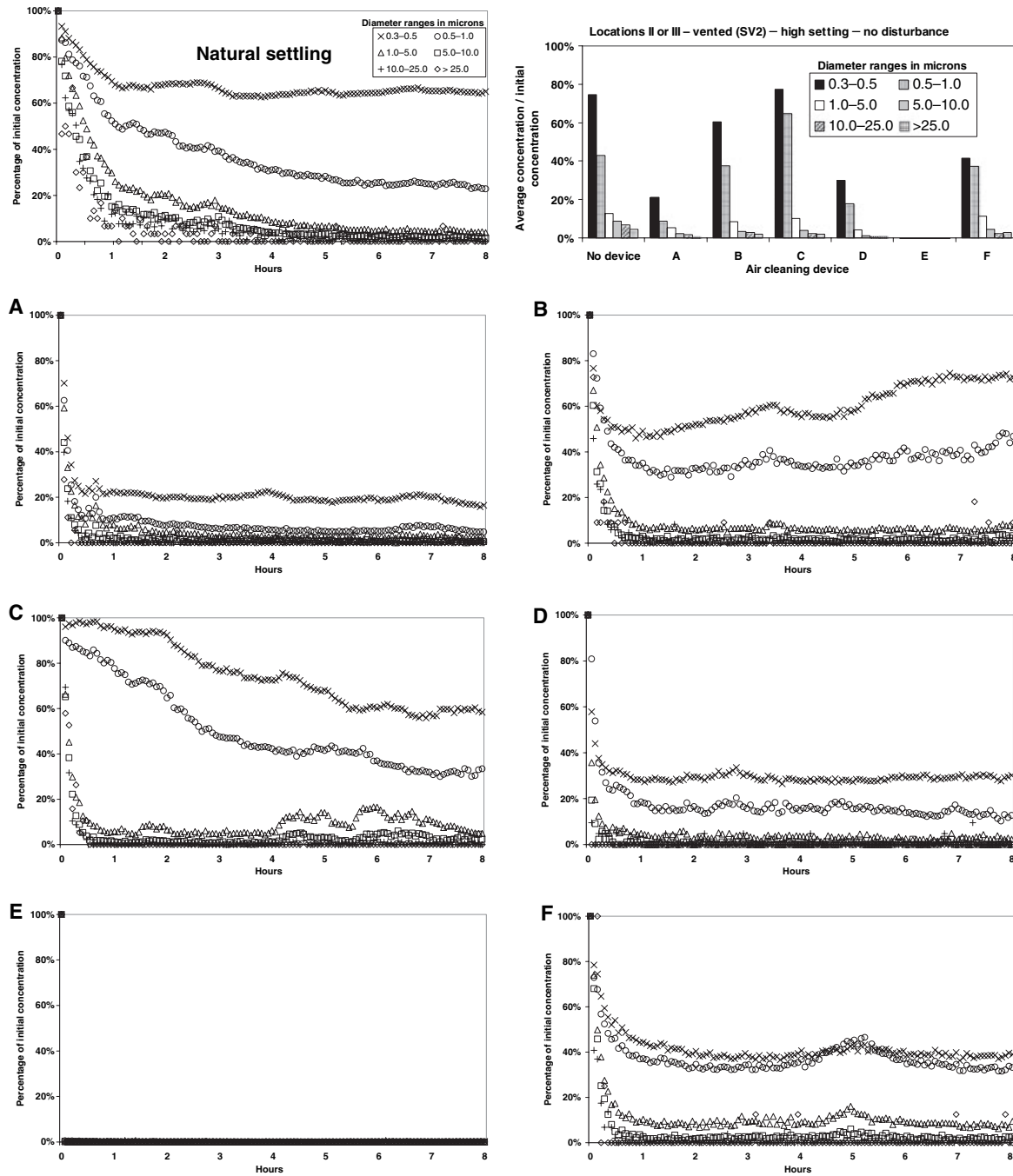


Fig. 4 Timewise concentrations and time-averaged concentrations for the specific conditions of: (i) device location: location III (Figure 1) for the portable devices and at the headboard (location II) for device E, (ii) controlled airflow: supply vent 2 and outlet grille (Figure 1), (iii) high setting for all of the air-cleaning devices, and (iv) no imposed disturbance

common with the corresponding graph in Figure 3, all of the larger particulates settle out, but perhaps not quite as rapidly in the presence of an air throughflow. The smaller particles display a residual concentration that is more or less the same for the conditions of Figures 3 and 4. With regard to the performance of devices A through F, it is noteworthy that devices C and E indicate performances that are virtually the same for the two operating modes respectively corresponding to Figures 3 and 4. Device B performs less

effectively, while devices A, D, and F show only moderate differences with respect to the two different operating modes. Overall, the least-effective devices for the conditions of Figure 4 are B and C, whereas device E continues to be the very best.

Examination of the time-averaged data conveyed at the upper right in Figure 4 supports the aforementioned observations. Devices B and C appear to offer little difference compared with natural settling, whereas the others offer some improvement, with the order of

improvement, from least to most, proceeding from F to D to A and to E.

The last of the composite figures which show both time varying and average results is Figure 5. The operating condition corresponding to this figure is unique in that a periodic disturbance generator, activated at 20-min intervals, was situated on the bed adjacent to the designated microenvironment volume. It is the presence of the imposed disturbances that lends the appearance of scatter to all of the time-

varying graphs of Figure 5. The operating conditions for Figure 5 are, aside from the imposition of the forced disturbances, identical to those for Figure 3. If attention is first turned to the case of natural settling (upper left of Figure 5), the interpretation of the presented results is aided by distinguishing between the particle concentration corresponding to the moment of the imposed disturbance and the particle concentrations during other times. For all six particle-size ranges, there is an instantaneous rise in

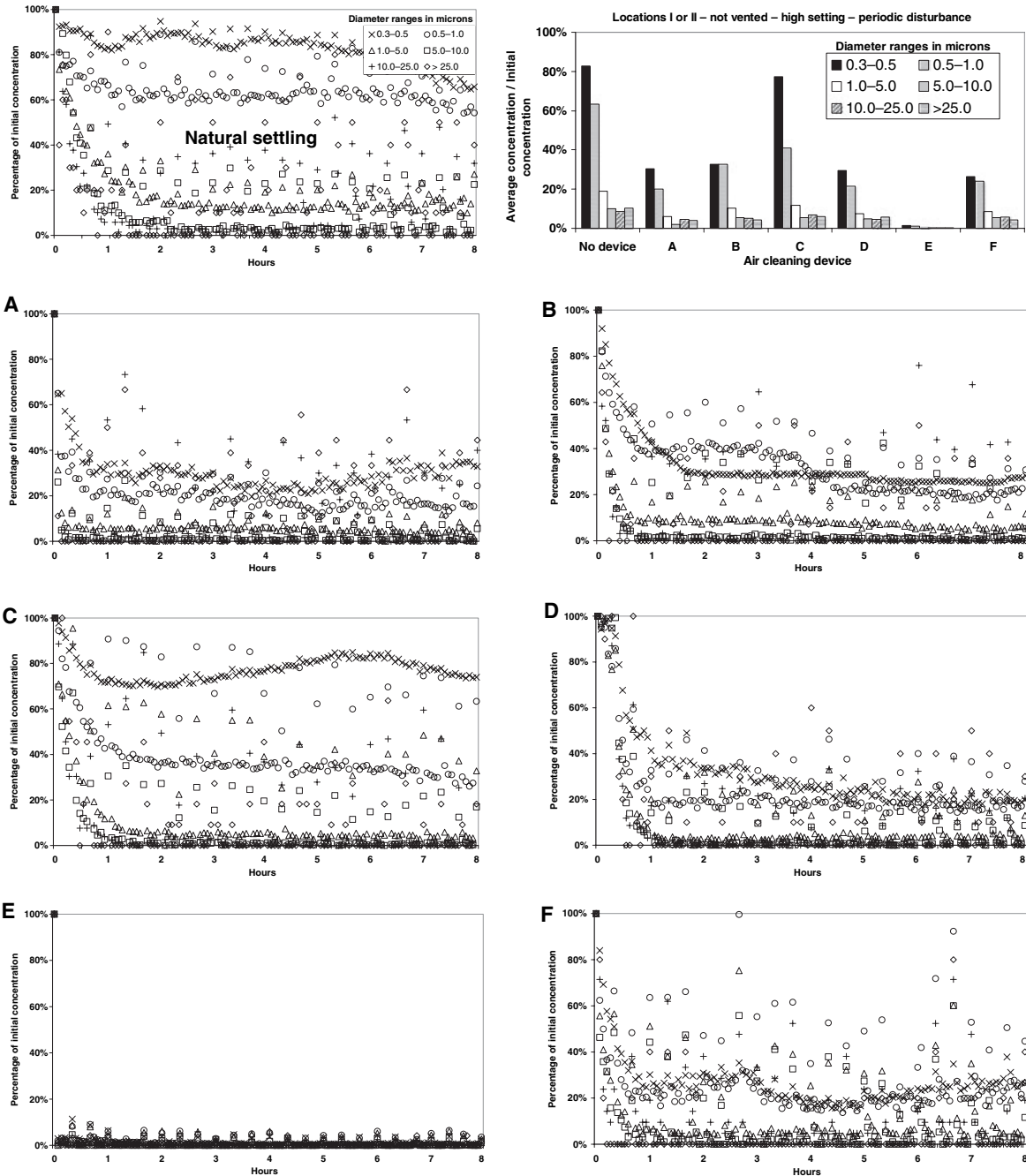


Fig. 5 Timewise concentrations and time-averaged concentrations for the specific conditions of: (i) device location: beside the headboard (location I) for the portable devices and at the headboard (location II) for device E, (ii) neither ingress or egress of air in the laboratory space (not vented), (iii) high setting for all of the air-cleaning devices, and (iv) periodically imposed disturbances

concentration at the moment of the disturbance application. The three largest particle-size ranges are able to settle naturally during the 20-min period prior to the next disturbance. For these ranges, the apparent scatter reflects the particle concentration measurement immediately after the disturbance. For the three smallest particle-size ranges, the 20-min period between disturbances is not sufficient for natural settling. Therefore, for these ranges, there are data showing a residual background spanning all times.

Next, if focus is shifted to the performance graphs for devices A–F in Figure 5, it is appropriate to consider both the capability of the respective devices to cope with the instantaneous burst of particulates associated with the disturbances and the capability of the device to deal with the interim period between disturbances. An overall inspection of all the device-related graphs of Figure 5 shows that device E is the most capable to deal with the burst itself, whereas device C reflects very little capability to respond to a burst. With regard to the non-burst background, device E seems to be the best while device C is, once again, the least effective.

The time-averaged results shown at the upper right of Figure 5 are best compared with the corresponding graph in Figure 3 in order to discern the impact of the periodic particle bursts. Especially noteworthy is the fact that there is a significant percentage increase in the average concentrations of the larger particles, although their actual amounts are small. The rank ordering of the relative performances of the air-cleaning devices remains as before, with device E being the very best and device C being the least effective.

Time-averaged concentrations

The presentation of results conveyed by Figures 3–5 has demonstrated that the broad conclusions drawn from observations of timewise concentration variations are corroborated by the time-averaged data. Therefore, in order to maintain a concise presentation, the following presentation of results will feature only time-averaged data.

Figure 6 displays the time-averaged data for all of the 10 operating conditions which were investigated. The information presented in Figure 6 was obtained by timewise integration of the available timewise concentration results such as those exhibited in Figures 3–5. Due to journal space limitations, all of the available timewise information could not be shown in the paper. However, the results conveyed in Figure 6 encompass all of the available timewise data.

The left-hand column of graphs in the figure relates to operation of the air-cleaning devices at their low settings, while the right-hand column conveys corresponding information for the high settings. The first and second rows of graphs correspond to different loca-

tions of the portable air-cleaning devices, under conditions of no forced disturbances and no airflow within the test environment. The issue of air throughflow is addressed in the third and fourth rows of graphs. The bottom row of graphs corresponds to the presence of imposed, periodic disturbances.

An overall view of Figure 6 reveals that the performance of devices D and E are nearly insensitive to the 10 investigated operating conditions, while the greatest sensitivity is displayed by devices B and F. In general, the use of the high setting for all of the devices yields performance that is either equal to or better than the performance at the low setting. Similarly, for the five portable air-cleaning devices, the performance as measured at the selected microenvironment volume when the cleaning device was situated near the headboard (location I) was equal to or better than the performance when the device was situated more remotely (location III). With regard to the presence or absence of air throughflow as represented by venting via either vent location I or vent location II, the effect of throughflow is not totally consistent. The direction of the effect (improved or diminished performance) appears to depend on the path of the throughflow and on the location of the air-cleaning device. The impact of the imposition of periodic disturbances is best assessed by comparing the top and bottom rows of graphs. As a general trend, it is seen that the larger particle groups are less well eliminated in the presence of the forced disturbances than in their absence.

From an overall comparison of the six air-cleaning devices operating under 10 independently controlled conditions, a rank ordering of the capabilities of the devices for a particulate-free microenvironment suitable for relief from the symptoms directly related to allergic rhinitis and asthma during sleep can be established. The resulting rank ordering is, from best to least: E, A/D, F, B, and C. This performance ranking, at least as regards device E, can be explained by the fact that E appears to have been specially designed to provide particulate-free air in the sleeper's breathing zone whereas the other devices were intended for overall, room-wide air cleaning.

Device particle removal efficiency

An alternative approach to the characterization of the air-cleaning capability of the respective devices is to evaluate an efficiency for each. The efficiency to be used here has already been defined in Equations 1 and 2. Inspection of those equations indicates that they define an efficiency which characterizes the device *per se* but not with respect to the task which is the essence of this paper (capability of the respective devices to create a specific, particle-free microenvironment). As already discussed, microenvironment is the breathing zone of a sleeping person.

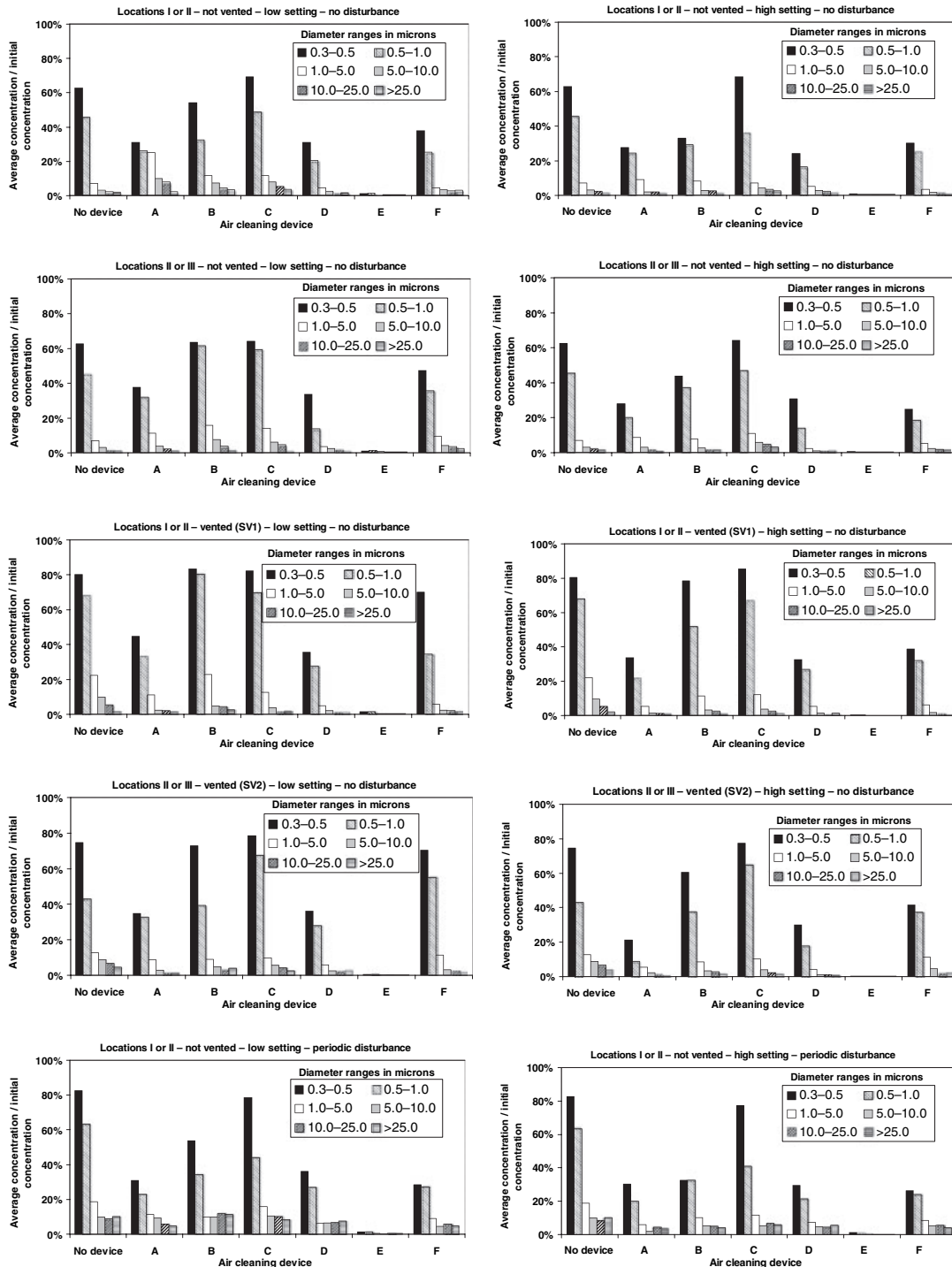


Fig. 6 Time-averaged particle concentrations for all of the 10 operating conditions that were investigated

The method used here to evaluate the efficiency defined by Equations 1 and 2 was to operate each device in the steady state and to measure the particle concentration of the inflowing and outflowing air-streams with respect to that device. The results obtained from these measurements in conjunction with Equation 2 are listed in Table 5. The numerical values appearing in the table correspond to particle sizes in the PM_{10} range.

Inspection of the table reveals that the three HEPA filter-based devices provide excellent filtering efficiency. In particular, devices D and E remove more than 99% of the particles that enter the respective device. The third of the HEPA filter devices, F, filtered out about 97% of the particles. In contrast, the electrostatic filter-based devices did not, as a group, perform as well. Among these, device A stood out as the best because it contains a multitude of electrostatically charged plates,

Table 5 Device efficiency at removing particles

Device	Particle removal efficiency (%), Equation 1
A	95.9
B	38.0
C	73.4
D	99.5
E	99.9
F	97.3

a much greater number than those that are used in devices B and C.

The data that are conveyed by Table 5 relate to the device-level performance and not to the system-level performance that is the focus of this investigation. By system-level performance, it is meant the capability to create a particle-free volume at a specified location. That capability is exhibited in Figures 3–5 rather than in Table 5.

Sound intensity results

The suitability of an air-cleaning device for therapeutic use not only depends on its capability of creating a suitable particulate-free microenvironment, but also on its lack of intrusiveness in the sleeping environment. The issue of intrusiveness is strongly dependent on the sound intensity produced by the air-cleaning device. Another important factor which influences the degree of intrusiveness is the nature of the coverings of the enclosing surfaces of the room and the texture of the furniture and its placement. The test space (the simulated bedroom) was bounded by hard-surfaced walls and ceiling. The floor, another hard surface, was covered by a rug which spanned two-thirds of the area. The bedclothes were soft-surfaced while the other furniture in the room was hard-surfaced.

To address the issue of sound intensity, measurements were made at the site within the selected sleeping microenvironment that coincided with the location at which particle concentrations were measured. The sound sensor was situated on the pillow of the bed. It was carefully positioned in an identical manner for all of the experiments. The sensing head was oriented in the direction of the location of the air-cleaning instrument.

The results of the sound measurements, characterized in terms of decibels, are summarized in Table 6. The table is subdivided into three parts, respectively for air-cleaning devices at locations I, II, and III (see Figure 1).

With regard to the portable devices, a distinction has to be made between location I, which is adjacent to the headboard, and location III which is in a far corner of the room. At location I and at the high setting, the sound intensity levels of the portable devices were, except for C, in the 60-dBA range. Device C was not

Table 6 Sound intensity results for each device at various locations (dBA)

	A	B	C	D	E	F
Location I						
High	63.5	61.0	<40	66.0	—	60.0
Low	55.0	<40	<40	<40	—	44.0
Location II						
High	—	—	—	—	46.0	—
Low	—	—	—	—	<40	—
Location III						
High	58.0	57.5	<40	62.0	—	55.3
Low	48.0	<40	<40	<40	—	<40

Table 7 Delivered device airflow data m³/min (ft³/min)

Device	Measured values		Manufacturer's given values	
	Low setting	High Setting	Low setting	High Setting
A	6.63 (234)	10.34 (365)	6.37 (225)	10.34 (365)
B	1.19 (42)	3.82 (135)	—	3.82 (135)
C	~0	~0	—	—
D	1.98 (70)	13.03 (460)	2.49 (88)	12.74 (450)
E	1.64 (58)	2.38 (84)	1.56 (55)	—
F	1.56 (55)	3.23 (114)	—	4.25 (150)

—, Not available.

fan-equipped. Device E, which was situated just above headboard height, had the lowest decibel rating of all of the fan-equipped, air-moving devices. When the portable air-cleaning devices were situated remotely from the sound measurement site, their perceived sound production was diminished from that measured when the respective devices were situated at location I. The results presented in the table are intended to be comparative with respect to the physical characteristics of the simulated room and do not represent the absolute sound production of the investigated devices.

The results conveyed in Table 6 and discussed in the preceding paragraph may be compared with the ASHRAE-recommended value of 40 dBA for a quiet residential area (Lorsch et al., 1997).

Device airflow

Several of the investigated devices specified the rate at which air passed through the device. With a view toward corroborating the given information, independent airflow measurements were made as part of this investigation. The corresponding results are presented in Table 7. The table shows that there is generally good agreement between the manufacturer-specified airflow rates and those that were measured independently here.

Concluding remarks

A comprehensive experimental study has been performed to evaluate the capabilities of several available

air-cleaning devices to provide a particulate-free microenvironment as a therapy for allergic rhinitis and asthma during sleep. During the course of the investigation, the impact of a number of independent parameters on the particle concentration in the specified microenvironment were investigated. The investigated parameters included: (i) device location, (ii) controlled air motion in the laboratory, (iii) airflow rate setting of the air-cleaning device, and (iv) controlled disturbances. Ten different operating conditions were employed. The air-cleaning capabilities of the selected devices were evaluated by the measurement of airborne particle concentrations in the microenvironment. A second consideration in the rating of the various devices was the sound intensity measured in the microenvironment.

Six different air-cleaning devices were evaluated. The air-cleaning methods of the selected devices included either HEPA filtering or electrostatic precipitation. Of the six, five were portable and were intended to provide general air cleaning for bedroom-sized rooms. The sixth was designed to be situated in front of the

headboard of a standard bed and to focally affect the particulate population for sleeping persons.

The presentation of results for particulate concentrations provided information on the air-cleaning capabilities of the selected devices in six different particle-size ranges. The variation of particle concentration as a function of time over an 8-h, sleep-simulating period is presented for each of the air-cleaning devices as well as for the natural settling of particulates in the experimental facility. Also presented are time-averaged particulate concentrations.

On the basis of the presented results, it was possible to rank order the various devices with respect to their capability of creating a particle-free sleeping space that could provide effective therapy for allergic rhinitis and asthma. It was found that the device designed to focus the cleaned air in the sleeping space fulfilled its goal and, in that regard, was clearly superior to all of the other air-cleaning devices. It was also found that the sound intensity of the superior air-cleaning device was generally lower than those of the other fan-equipped devices.

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