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Effectiveness of Airborne Fungi Removal by using a HEPA Air Purifier Fan in Houses

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Few studies have evaluated the performance of air purifiers in removing airborne fungi in houses. Here, we evaluated the ability of a HEPA air purifier fan to remove airborne fungi in six houses in Japan. In each house, the number of airborne fungi decreased more rapidly when the air purifier fan was on (test measurement) than when it was off (control), demonstrating its ability to decrease the fungal concentration. The number of airborne fungi decreased between 1.5 and 6 times faster when the air purifier fan was on than when it was off (spontaneous decrease). Clean air change rates, calculated from measurements taken 15 min after the test equipment operation began, ranged from 2.9 to 5.4 (h^{-1}), indicating adequate air cleaning. One of the six test houses contained a much greater concentration of airborne fungi than the standard set by the Architectural Institute of Japan. When the air purifier fan was operated in the house, the indoor/outdoor (I/O) ratio decreased from 77.5, equating to a fungal concentration of 53,000 cfu/m^3 at 0 min to 0.72 or 620 cfu/m^3 after 45 min, which is below the standard. This reduction clearly demonstrated the anti-fungal effect of the air purifier fan.

Key words：Airborne fungi / Air Purifier / HEPA / I/O ratio.

INTRODUCTION

Japanese people show keen interest in the microbial contamination of air in houses, and many products to remove airborne microorganisms are available. There are a number of guidelines for measuring the effectiveness of products such as air cleaners in removing airborne microbes, including JEM1467: Specifications of The Japan Electrical Manufacturer's Association (JEMA, 2015), JACA No.50: Guideline for performance evaluation of air cleaners (JACA, 2016), and SIEJ Standard Method No. 20110001 of the Society of Indoor Environment, Japan (SIEJ, 2012). Experimental results measuring adherence to these specifications are considered evidence for the removal of airborne microbes by various products distributed in the Japanese market. Such experiments are performed in a closed chamber to minimize any fluctuations in the number of airborne microbes due to external factors. However, houses are less airtight than a closed chamber. They contain obstacles, such as furniture, and sources of microbes. The house environment is clearly different from that of a chamber; however, there have been few studies evaluating products for their ability to remove airborne microbes in houses. Increasing the air flow (m^3/h) and the rate of microbe capture (%) using an air cleaner may decrease the concentration of airborne microbes (cfu/m^3) in a house. However, the amount of in-house microbe generation (cfu/h) and ventilation (m^3/h), which affect the microbial concentration, differ markedly among houses (AIJ, 2013a). Therefore, it is difficult to determine how much of an effect the increased air flow and capture rate from air purifiers would exert. To address this question, this study examined the performance of a HEPA air purifier fan in six houses in Japan. Measurements were taken in each of the test houses to identify variations in the concentration of naturally-occurring airborne fungi. One of the houses was found to contain fungi at a far higher level than the standard set by the Architectural Institute of Japan, which enabled evaluation of the performance of the air cleaner

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in a highly contaminated environment.

MATERIALS AND METHODS

Air purifier and testing environment

Testing was performed in six houses located in the suburbs of Tokyo (Tokyo, Kanagawa, and Chiba) in August and September 2015 (Table 1). The test environments were living rooms with wood flooring. A HEPA air purifier fan by Dyson Pure Hot and Cool (N264a; Dyson Limited, Wiltshire, UK) was used in the test. HEPA and activated carbon filters were added to a series of products marketed as fans for cleaning air (Fig.1). Unlike stationary air cleaners, which draw in air but do not produce much air circulation, the wide air outlet and rotational motion of the fans caused circulation of air in a large room by convection. As each room had a floor area measuring approximately 12 m^2, we used an air purifier fan with the capacity needed for a floor space of 12-13 m^2.

Control measurements

Control measurements were taken to examine the rate of spontaneous decrease in the number of airborne fungi due to falling and natural ventilation (Kuriyama et al., 2002; Ono et al., 1987; JACA, 2016). Windows and room doors were closed to initiate the test. The cleaner was placed 1 m from the wall when possible given furniture placement. Airborne fungi were sampled in accordance with the methods set out in AIJES-A0002-2013 and AIJES-A0008-2013 Environmental Standards of the Architectural Society of Japan (AIJ, 2013a; 2013b). Air sampler (SAS SUPER 100; Pbi International, Milan, Italy) with DG18 agar (Merck, Darmstadt, Germany) were positioned at three locations, one in the center of the room and two in room corners (50 cm horizontal distance from the wall), to sample airborne fungi. The sampler was positioned at a height of 1.2 m from the floor and set to draw 50 L of air (flow rate 100 L/min). Sampling was performed at 0, 15, 30, and 45 min, and was repeated a total of four times. Electricity was switched off for the duration of the control measurements. An air sample was also taken outside the house following each in-house measurement.

Test measurements

The test commenced once windows and room doors were closed and the purifier fan was turned on (air flow 10 (200 ℓ/sec.), oscillation feature on). The same procedure was followed for both the control and test measurements.

Culturing and identification

Fungi collected on DG18 plates were cultured at 25℃ for 7 days for subsequent counting. Isolates were identified based on their colony and microscopic characteristics after subculturing on PDA (potato dextrose agar; Nissui, Tokyo, Japan), MEA (malt extract agar; Difco, Detroit, USA), CYA (czapek yeast extract agar; Samson et al., 2004), and M40Y agar (malt yeast 40% sucrose agar; Samson et al., 2004) plates. Fungi in the genus *Aspergillus* were identified based on the description of Raper and Fennell (1965) and Klich (2002). The other fungi were identified based on the description of Samson et al. (2004).

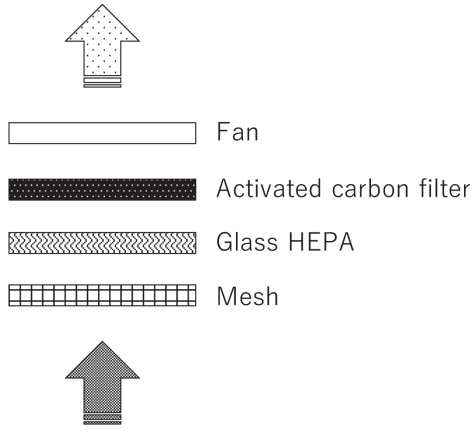

FIG. 1. Schematic diagram of filter configuration.

TABLE 1. Characteristics of the houses in this study.

House ID	Prefecture	Living arrangement	Effective age [years]	Room type	Floor number	Area [m^2]	Volume [m^3]	Examination date
A	Kanagawa	Detached house	16	Living room	2F	12	29	August 2015
B	Tokyo	Detached house	5	Living room	2F	12	29	August 2015
C	Kanagawa	Detached house	16	Living room	2F	12	30	August 2015
D	Kanagawa	Apartment	12	Living room	2F	13	33	August 2015
E	Kanagawa	Detached house	19	Living room	2F	12	29	August 2015
F	Chiba	Detached house	28	Living room	3F	11	17	September 2015

RESULTS AND DISCUSSION

Changes in airborne fungal concentrations

Fig.2 shows changes in the number of fungi per cubic meter of air in the six test houses (A to F). Feller's formula (Feller, 1950; Karwowska, 2005) was used to correct for coincidence loss in the number of isolated colonies. Values from the three sampler locations were averaged to determine the concentration of total airborne fungi. For all the houses, the test measurements exhibited steeper slopes than the controls, meaning that the number of fungi decreased faster in the test measurements than in the controls. These results showed that the air purifier fan decreased the number of airborne fungi in the test environments. When the air was cleaned to high levels, the effect became difficult to discern. In houses B and D, fungal concentrations reached the lower limit within 30 min, as shown by the slopes of the straight lines and correlation coefficients, and therefore the approximation curves do not include a 45 min time point. The residual ratio (%) of each fungal concentration was calculated and the ratios for the six houses were plotted on a graph (Fig.3). The distributions of the control and test measurements showed clear differences in the rate of fungal spore reduction. In addition, the half-life (Tb) (log 0.5/slope) for the control measurements and the half-life (Tt) for the test measurements were calculated. Tt was divided by Tb (Tt/Tb) to determine the relative rate of decrease in fungal spores. We found that the number of fungal spores in house A

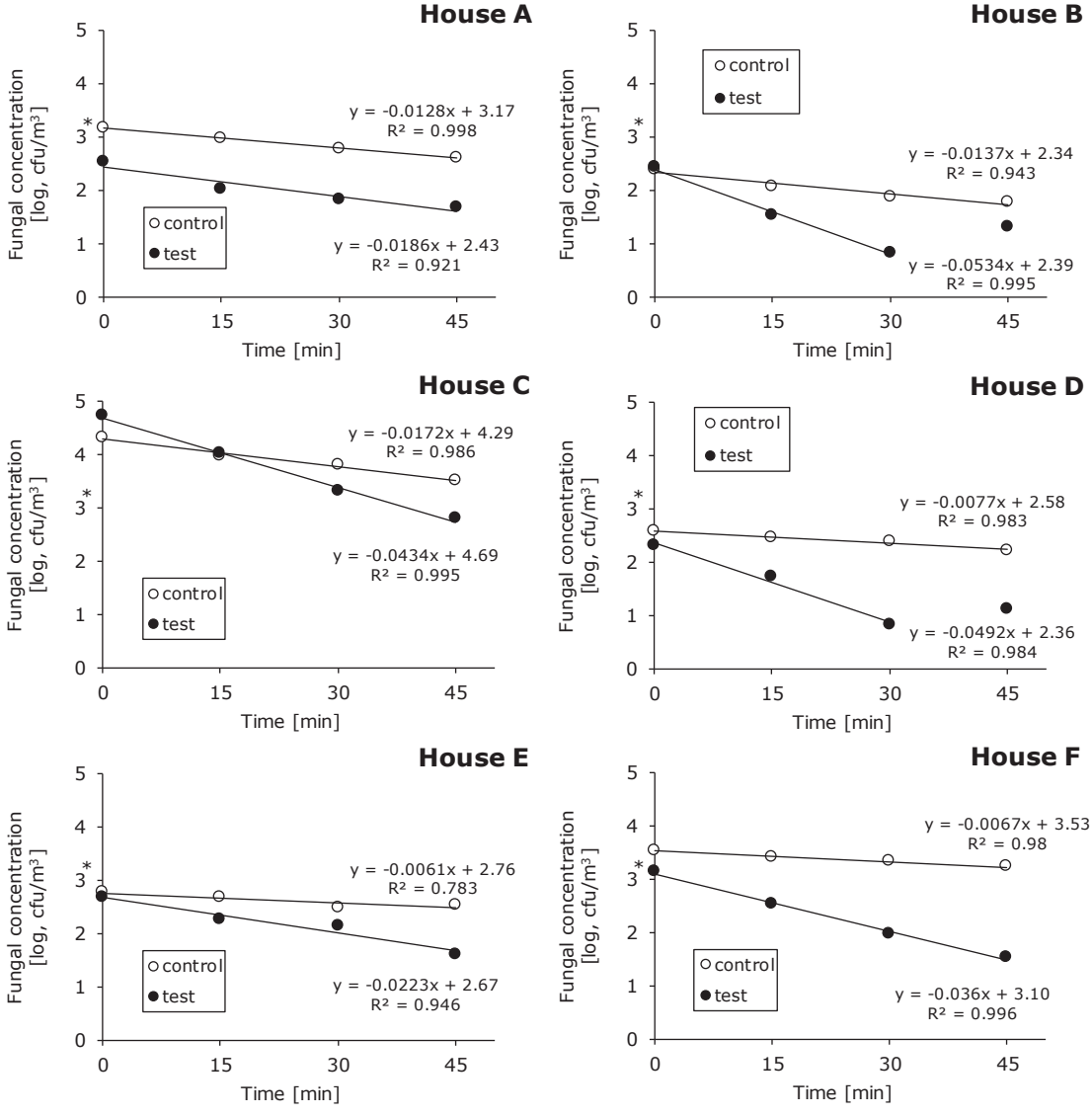

FIG. 2. Changes in the airborne fungal concentrations in each house.
*The standard value of AIJES is set to 1000 cfu/m^3 or less.

decreased 2.1 times more rapidly in the experimental tests than in the control tests. Similarly, fungal spore numbers decreased 4.7 times faster in the test measurements compared with the control tests in house B, 2.8 times faster in house C, 6.2 times faster in house D, 3.6 times faster in house E, and 5.6 times faster in house F.

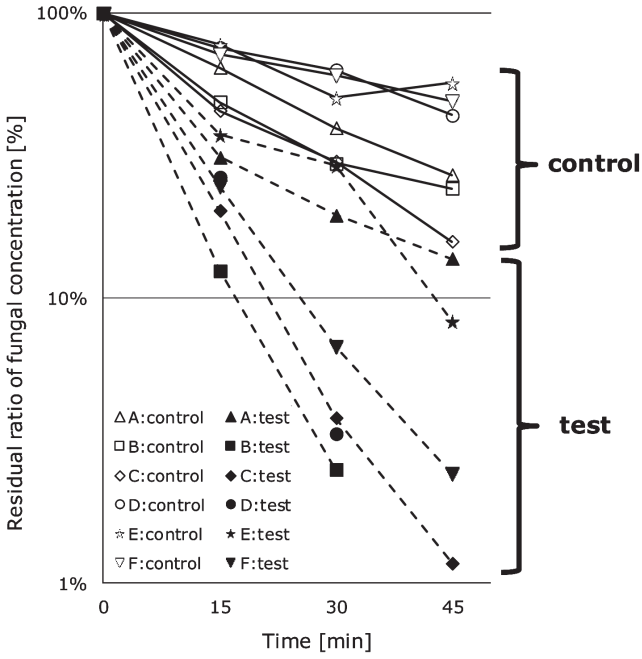

FIG. 3. Changes in the residual ratio of fungal concentration in each house.

Fungi present in the houses varied in kind (Table 2). Fungi in the genus *Penicillium*, which form minute spores ranging from 1 to 2 μm in size (Samson, 2004), and the genus *Alternaria*, which form spores as large as 25-40 μm (Samson, 2004), were observed. Airborne spores of all sizes were found to decrease in concentration after the air purifier fan was turned on (Table 2).

Clean air change rate calculations

The clean air change rate (h^{-1}) is used as an indicator for indoor air-cleaning ability. The airborne fungal concentration for each house is substituted into the following mass balance equation (JACA, 2016) to calculate the clean air change rate (h^{-1}), N.

$$Q'_{eq} = -\frac{V}{t}\left(\ln\frac{C(t)_{AC}}{C(0)_{AC}} - \ln\frac{C(t)_{BL}}{C(0)_{BL}}\right)$$

$$N = \frac{Q'_{eq}}{V}$$

N : clean air change rate (h^{-1})
Q'_{eq} : equivalent clean air rate (m^3/h)
V : air volume of room (m^3)
t : measured time (h)
$C(0)_{BL}$: control fungal concentration (cfu/m^3) at the beginning of measurement

TABLE 2. Major fungi and their concentrations after 0 and 45 min of air purifier operation in each house.

	Airborne fungul concentration [cfu/m^3]											
	A		B		C		D		E		F	
Genus, Section or Species	0 min	45 min	0 min	45 min	0 min	45 min	0 min	45 min	0 min	45 min	0 min	45 min
Alternaria spp.	6.7		6.7		20							
Aspergillus spp. (total)	40	13		6.7	8100	550	13	6.7	27		67	6.7
A. section *Aspergillus*[a]											13	
A. japonicus					33				6.7		13	
A. niger	13								6.7		6.7	
A. section *Restricti*	27	13			8000	550	13	6.7	6.7		33	6.7
A. versicolor				6.7					6.7			
Aureobasidium spp.					6.7							
Cladosporium spp.	100	13	73	6.7	350	6.7	80	6.7	150	20	620	
Fusarium spp.	6.7										6.7	
Paecilomyces variotii							6.7					
Penicillium spp.	27	6.7	33		100	13			33		33	
Wallemia sebi							6.7				6.7	
Yeasts			73	6.7					33		20	6.7
Others	150	13	80			40	93		230	20	530	20

[a]Known as *Eurotium*

TABLE 3. Clean air change rate calculated from measured values at 15 and 30 min.

House ID	Volume [m^3]	Clean air change rate [h^{-1}]	
		15 min	30 min
A	29	2.9	1.4
B	29	5.4	5.0
C	30	3.2	4.1
D	33	4.2	5.9
E	29	2.9	1.1
F	17	4.3	4.4

$C(0)_{AC}$: test fungal concentration (cfu/m^3) at the beginning of measurement
$C(t)_{BL}$: control fungal concentration (cfu/m^3) at time t during measurement
$C(t)_{AC}$: test fungal concentration (cfu/m^3) at time t during measurement

Table 3 summarizes the clean air change rates (*N* values) calculated from measurements taken 15 and 30 min after the operation began. The ventilation rate stipulated for a house by the Building Standard Law of Japan is 0.5 (h^{-1}) (BCJ, 2015). The air purifier fan yielded *N* (h^{-1}) values 2.2 to 12 times higher than the stipulated value, demonstrating that the tested equipment could adequately clean air. No correlation was observed between *N* (h^{-1}) and room capacity, showing that *N* (h^{-1}) was largely influenced by the house environment. Although the *N* (h^{-1}) values measured for house F at 15 and 30 min were almost equal, this was not the case for other houses. Because the air volume of the room in house F was small, the airborne fungal concentration was uniform; on the other hand, in the case of large air volume of other houses. there was a concentration distribution of airborne fungi in the rooms, and it is presumed that this variation impacts the *N* (h^{-1}) measurements. The development of methods to obtain a uniform airborne fungal concentration may pose a challenge when evaluating these types of environments.

The airborne fungal concentrations were low in many houses. Therefore, necessary concentrations for accurate measurement could not be maintained for longer than 30 min (Fig.2). Yanagi et al. (2011) evaluated an air cleaner with an applicable floor space of 16 m^2 for removing airborne particles from a living environment, a room with an air volume of 38 m^3. The measured clean air change rate was 2.3 (h^{-1}). The decrease in the number of airborne particles began to slow 20-25 min after the air cleaning commenced; this finding agrees with the results from our study. Use of the earliest possible measurement time may yield more appropriate

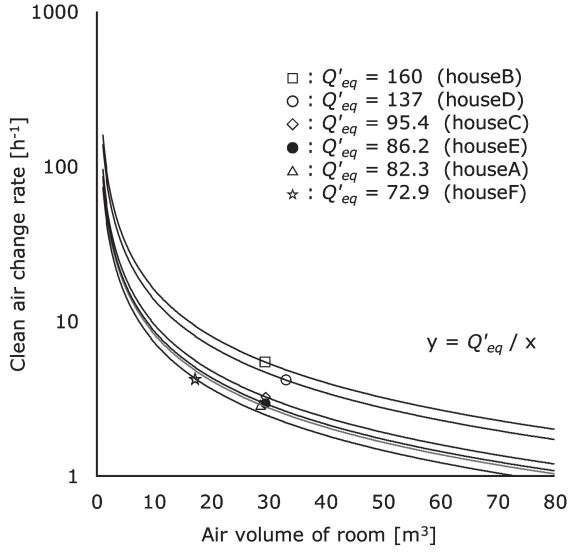

FIG. 4. Relationship between clean air change rate and room volume predicted from measuring the equivalent clean air rate.

data to determine the equivalent clean air rate or air change rate in an actual living space.

Fig.4 shows the clean air change rates predicted for varying room air volumes, with Q'_{eq} constant for each house. The clean air change rates were measured after 15 min, and the background airborne fungi were maintained at high concentrations. The amount of in-house fungi generation was presumed to be constant regardless of the air volume of the room. Fig.4 shows that the clean air change rate was higher and that cleaning was faster in rooms with smaller volumes. It also shows that a clean air change rate exceeding 1 (h^{-1}) can be achieved, even if the air volume of the room is nearly twice as large (60 m^3).

Efficiency of fungal spore removal from high-concentration polluted houses

As the concentration of airborne fungi in a house is influenced significantly by the outdoor air supply, it is difficult to set a standard value (AIJ, 2013a). Therefore, the ratio of the number of indoor fungi/outdoor fungi (the I/O ratio) is used as an indicator of the level of contamination with airborne fungi. An I/O ratio greater than 1.0 is considered to show the presence of indoor sources of fungal contamination. The AIJES-A0002-2013 Environmental Standard of the Architectural Society of Japan sets the standard for house management at a "concentration of airborne fungi at 1000 cfu/m^3 or less" and an "I/O ratio of 2.0 or less when the concentration of airborne fungi is 1000 cfu/m^3" (AIJ, 2013a). Considering this, only house C substantially exceeded the standard value. In house C, the control test value

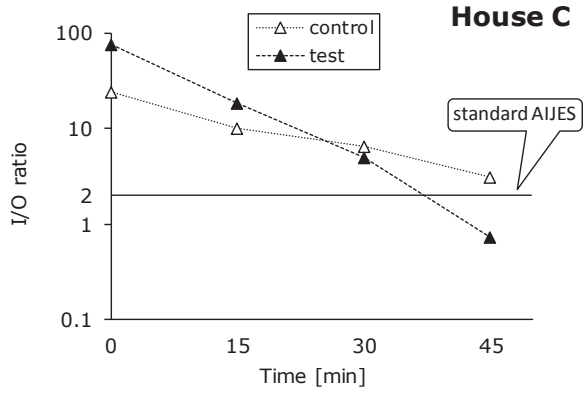

FIG. 5. Changes in the I/O ratio of airborne fungi in house C. Although the I/O ratio was 2 or more of the standards of AIJES-A0002-2013 (AIJ 2013a), it decreased to below the reference value after 45 min.

was 21,000 cfu/m^3 at 0 min and the I/O ratio was 24.1; even in a room tightly closed to accelerate the reduction in levels of airborne fungi, the concentration was 3,300 cfu/m^3 and the I/O ratio was 3.1 after 45 min, exceeding the standard (Fig.2 and 5). These data demonstrate that house C was contaminated with a high concentration of fungi. Contaminating fungi were mostly *Aspergillus* section *Restricti* (Table 2). This is a typical fungus contained in house dust (Visagie et al., 2014) and is often present in high concentrations in Japanese houses (Hashimoto and Kawakami, 2015).

An air purifier fan in operation in house C for 45 min reduced the concentration of airborne fungi from 53,000 cfu/m^3 (I/O ratio of 77.5) at 0 min to 610 cfu/m^3 (I/O ratio of 0.71), which is below the Environmental Standard of the Architectural Society of Japan (Fig.2 and 5). This result demonstrates that the operation of a suitable air purifier fan can not only decrease the concentration of airborne fungi, but can also bring a highly elevated concentration within a normal range.

However, the air purifier fan, like many other air cleaners, is only effective during the operation period; it does not elimina te sources of fungal contamination. Air cleaners do not provide a fundamental solution to fungal contamination.

Previous studies (Cheng et al., 1998; Kuriyama et al., 2002; Ono et al., 1987) considered the presence or absence of air cleaners and fluctuations in airborne fungi concentrations, but the effectiveness of the air cleaners was not clearly demonstrated. The current study used the clean air change rate (h^{-1}) and I/O ratio to compare test results against a recognized standard and clearly showed the effectiveness of an air cleaner in removing airborne fungi. Children are more likely to develop allergies in a house with an airborne fungal concentration that exceeds the standard set by AIJES-A0002-2013 (AIJ, 2013a). Allergic bronchopulmonary mycosis (ABPM) is an allergic condition caused by inhaling airborne fungal spores (Greenberger, 2002). Oshikata et al. (2017) surveyed a house accommodating an ABPM patient and recorded a high concentration of airborne fungi exceeding 10^5 cfu/m^3. They reported that removal of the fungal contamination improved the patient's symptoms. We expect that daily operation of a HEPA air purifier fan in a living space would contribute to the management of allergies caused by inhaling fungi.

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