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Research Article

Experimental Verification of the Particle Blocking Feature of Nasal Hair

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ABSTRACT Although it is well known that nasal hair keeps particles from entering our body, its quantitative evaluation has not been done. In this study, the particle blocking efficiency by nasal hair was studied both experimentally and numerically. The results of laboratory experiments performed with the successfully reconstructed artificial nose indicate that nasal breathing is effective in blocking particle (especially the giant particle lager than 5 μm), especially during the exercise respiration mode. At the exercise respiration pattern, two kinds of coarse particles (i.e., particles of 2–5 μm and >5 μm) showed a continuous decrease in particle blocking efficiency (E_{pb} (%)) with increasing breathing duration. All curves drown by the theoretically calculated particle cut-off efficiency of nasal hairs ($E_{integ.}$) with three different thicknesses (i.e., 50, 75, and 100 μm) show a minimum (nearly zero) for the particle ranged from 0.004 to 0.4 μm. In the $E_{integ.}$ curves, the thinner nasal hair can block particles more efficiently through a whole particle size range.

KEY WORDS Nasal hair, Particle, Health effect, Particle blocking, Inhalation

1. INTRODUCTION

The presence of ambient artificial particulate matters (PM) and allergenic biological pollens has been one of the main causes of adverse effects on air quality as well as human health. The air quality deterioration by PM in urban area has become of increasing public concern because of its importance and sensitivity related to health risks (Schwartz and Neas, 2000). The fine PM can penetrate the deeper human body via the pulmonary tract. The finest particles can even reach the cardiovascular system. PM_{10} can disturb the mucous secretion in the respiration system, cause breathing problems and increase the susceptibility to infections of the respiratory tract (Anderson *et al.*, 2005).

The World Health Organization (WHO) postulates that short exposure to high concentrations of PM may have following effects: inflammation of lung tissue, effects on the respiratory tract, detrimental effects on the cardiovascular system, an increase in the use of medication, hospitalization, and mortality. Long-term exposure to lower concentrations of PM may also cause negative health effects. The WHO poses there is an increased risk for respiratory diseases and decreased life expectancy because of cardiopulmonary (heart and lungs) mortality and probably also because of lung cancer. These effects are more pronounced in elderly people, children or persons with heart, immunity or respiratory afflictions (Rückerl *et al.*, 2011).

Our body has several organs with a great feature that work to defend our body against harmful PM. Adult humans have hair in the interior nasal passage. Hair in the nose (hear after called as "nasal hair") is one of the body's first lines of defense against harmful environmental pathogens such as germs, fungus, and spores. Ozturk *et al.* (2011) reported that increased nasal hair density decreases development of asthma in those who have seasonal rhinitis, possibly due to an increased capacity of the faces to filter out pollen and other allergens. Although the amount of nasal hair can vary between individuals, relatively large particles entering the nose are blocked by nasal hair present in the anterior nares. Increased nasal hair density can improve the particle blocking efficiency of the nose, while reduced amounts of nasal hair cause a decrease in its efficiency.

Till now, several studies about experimental and theoretical estimation of PM deposition on nasal cavity (Shang *et al.*, 2015; Liu *et al.*, 2010; Scott *et al.*, 1978) have been reported, however, there have been no studies that can experimentally verify the PM blocking feature of nasal hair.

Therefore, the main objective of this study was to verify the filtering function of nasal hairs for the entering foreign PM using the artificial nose model of our own manufacturing.

2. EXPERIMENTAL METHODS

2.1 Design of the Artificial Nose

There are many different shapes of human nose according to the width of the nostrils, the distance between nostrils, the height of the nose, nose ridge length, nose protrusion, external area of the nose, and the area of the nostrils. Also, each race has different nasal morphologies which result in variations of nasal airflow patterns and nasal functions (Zhu *et al.*, 2011). Therefore, the design of human nose is not simple. Moreover, no information of nasal hair density was reported. Thus, in the present study, the real human hairs (Hairdyrect/Japan Co.) that are commercially available for the purpose of increasing hair density were substituted. The commercial human hairs with the 95 μm thickness and 2 hairs 1

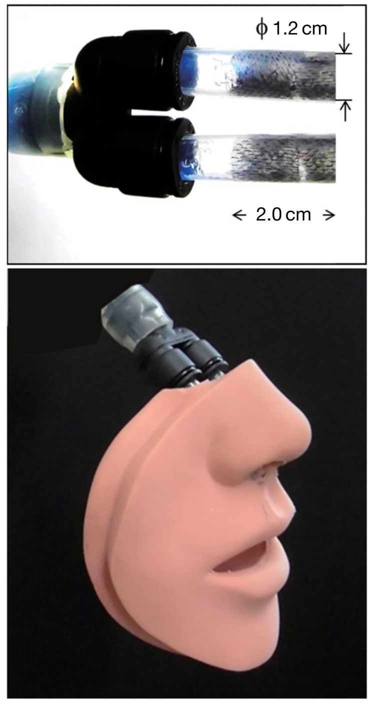

Fig. 1. The reconstructed artificial nasal valves (top) and its setting up to a part of face model (bottom).

mm^{-2} density were attached onto the inside of the artificial nostril designed in this study (see Fig. 1). The number of total nasal hair at both nostrils (expressed in terms of anatomy as the nasal valve area) estimated from the hair density and surface area of the designed nostril were 4,522. Unlike the reconstructed artificial nasal valves shown in Fig. 1, the actual nostril (i.e., nasal valve) is a highly complex structure. The internal nasal valve is the narrowest part of the airway in the middle third of the cavity. The larger external nasal valve is located in the alar wall (Becker and Becker, 2003). Thus, it is very difficult to reconstruct a more realistic anatomical structure. The reconstructed artificial nose (typically found in Asian (average the noses of adult male and female) morphologies (Becker and Becker, 2003)) was finally affixed to a part of the face model of the rescue training mannequins (see Fig. 1).

2.2 Laboratory Experiment

An experimental setup was designed in a closed experimental room (W2.5 × L3.0 × H2.4 m) at the Fukuoka Women's University in Japan. Fig. 2 shows the schematic diagram for laboratory experiment. The experimental setup consists of the reconstructed artificial nose, two

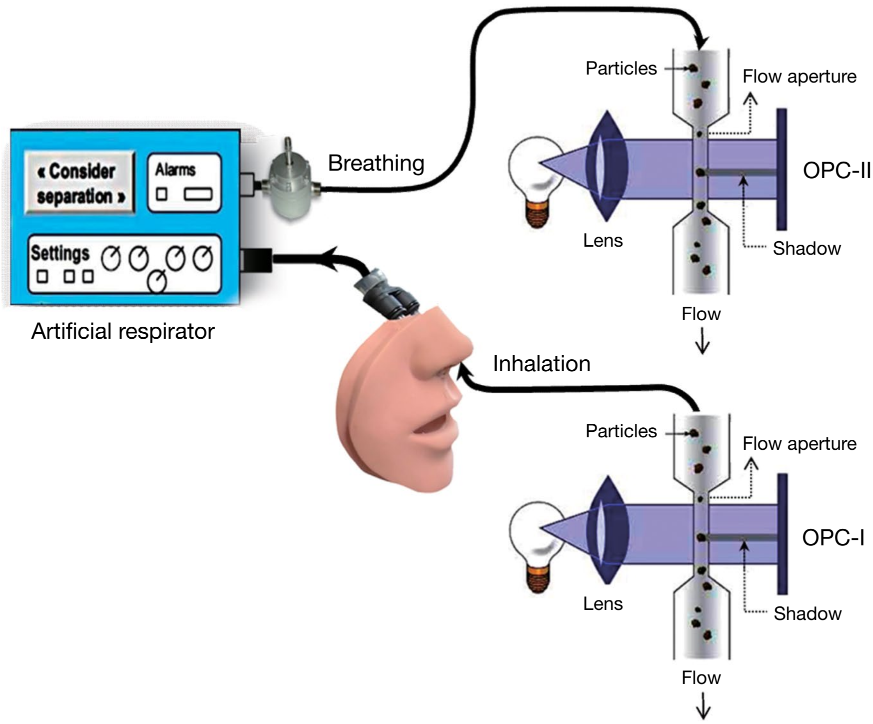

Fig. 2. Schematic diagram for laboratory experiment.

Table 1. The E_{pb} (%) of nasal hairs for two types of particle size according to breathing pattern.

Respiration pattern	Respiration volume[a] (mL time^{-1})	Respiration[b] (times min.$^{-1}$)	Inhalation rate[c] (mL s^{-1})	Particle size (μm)	Particle num. conc. (# L^{-1})		E_{pb} (%)[f]
					Before breathing[d]	After breathing[e]	
Rest	540	12	216	2.0–5.0 > 5.0	99 33	55 16	44.46 51.60
Ordinary	600	13	260	2.0–5.0 > 5.0	218 59	138 35	43.14 52.42
Exercise	900	21	630	2.0–5.0 > 5.0	105 29	58 12	44.88 56.83

$c = a\left(\frac{60}{b} \cdot \frac{1}{2}\right)^{-1}$

$f(\text{particle blocking efficiency}) = \frac{d-e}{d} \cdot 100$

optical particle counters (HHPC3+, HACH Co.), and an artificial respirator (ARF-900EII, Acoma Co.). In order to remove the dust material, the inner artificial nose was cleaned every time using a ultrasonicator before each experiment.

Because large particles entering the nose are collected by nasal hair present in the anterior nares (Becquemin *et al.*, 1991), in this study, two types of particle size (i.e., 2–5 μm and > 5 μm) were the target of the estimation. To assess the particle blocking efficiency for the real indoor particles, the actual particles present in a closed experimental room were applied instead of the artificially generate particles. The number size distribution of background particles at our closed experimental room was varied from 99 to 218 L^{-1} and 29 to 59 L^{-1} at a diameter of 2–5 μm and > 5 μm, respectively. According to three different types of breathing (i.e., rest, ordinary, and exercise), the respiration volume for once (Zuurbier *et al.*, 2009), inhalation flow rate, and respiration time varied as shown in Table 1.

2.3 Visual Observation

For the purpose of observing the morphology of the particles attached onto the nasal hairs, a SEM (JEOL JSM-5400) equipped with an EDX (Philips, EDAX DX-4) was employed. Some nasal hairs were placed inside the SEM's vacuum column (10^{-6} Torr) through an air-tight door. Particles were also distinguished and countered under 3,000 magnification and 15–20 kV working conditions.

3. RESULTS AND DISCUSSION

3.1 Particle Blocking Efficiency According to Breathing Patterns

Fig. 3 shows the SEM images of the particles attached onto an artificial nasal hair after laboratory experiment. As shown in Fig. 3, the nasal hair's particle capturing was visually confirmed. In the present study, taking into consideration the particle deposition onto an artificial respirator and particle density changes in the experimental room, we set a time limit of 10 minutes for the total test breathing. During experiment (10 minutes), no meaningful particle deposition at the inner artificial respirator was found.

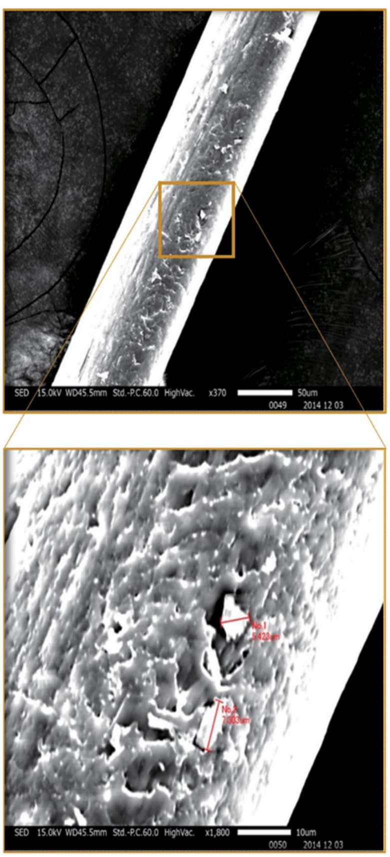

Fig. 3. SEM images of the particles attached onto an artificial nasal hair.

Table 1 summarizes the variation of particle number concentration for coarse particles of two different sizes (i.e., 2–5 μm and > 5 μm) before and after breathing as a function of respiration pattern. After having completed in breathing, particle number concentration at both sizes showed significantly lower levels. Particle blocking efficiency (E_{pb} (%)) of nasal hairs can be evaluated simply by measuring the number of inspired (OPC-I) and expired (OPC-II) particles in each breath. The E_{pb} (%) of nasal hairs for particles of 2–5 μm and > 5 μm varied from 43.14 to 44.88% and 51.60 to 56.83%, respectively. This result clearly indicates that nasal hair more effectively blocks the giant particles larger than 5 μm (such as soil particle and pollen), regardless of breathing pattern. High particle blocking feature for the giant particles was the expected result. However, it should be noted that while no significant change of E_{pb} (%) was shown at the particles of 2–5 μm, there was a continuously increasing at the particles larger than 5 μm in accordance with the increasing of respiration volume and time.

The fact that E_{pb} (%) of nasal hair for middle size particles was unchanged even though during exercise indicates that the considerable amount fine particles are easily inhaled into the deeper respiratory tract during exercise. For this reason, we must avoid a violent exercise during the episodically high $PM_{2.5}$ days.

It is suspicious point that after particles hit our nasal hairs, do they stay there? Or do they eventually get sucked in as we breathe more?

Table 2 shows the E_{pb} (%) of nasal hairs for two types of particle size according to breathing duration. In the

Table 2. The E_{pb} (%) of nasal hairs for two types of particle size according to breathing duration.

Respiration pattern	Particle size (μm)	E_{pb} (%) of each respiration duration		
		0–3 min.	3–6 min.	6–9 min.
Rest	2.0–5.0	42.26	43.88	42.39
	> 5.0	48.71	50.41	52.08
Ordinary	2.0–5.0	41.43	45.07	42.82
	> 5.0	47.10	57.16	51.84
Exercise	2.0–5.0	53.33	41.63	35.27
	> 5.0	67.83	55.11	40.49

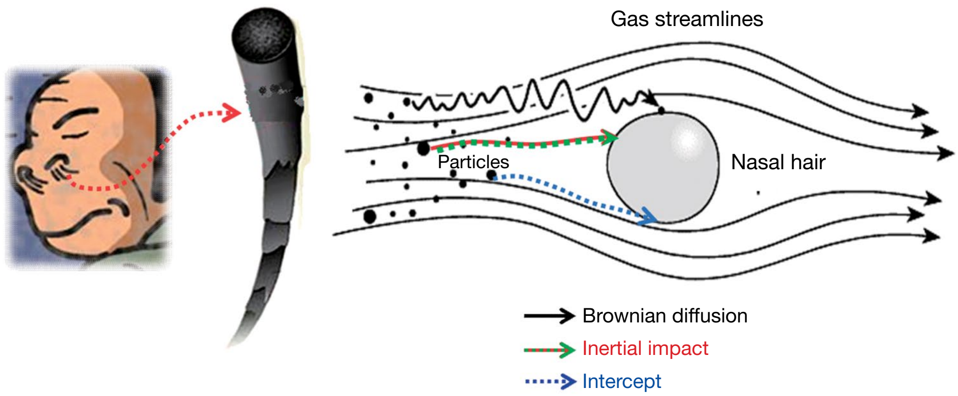

Fig. 4. Fundamentals of particle adhesion onto the nasal hair.

case of rest and ordinary breathing patterns, the particles of 2–5 μm has no significant variation of E_{pb} (%) during the 9 minutes initial respiration. It varied from 42.26 to 43.88% and 41.43 to 45.07% at rest and ordinary breathing patterns, respectively. Meanwhile, at the same breathing pattern, the giant particles marked a relatively high E_{pb} (%) with from 47.10 to 57.16% without no continuous fluctuation.

On the other hand, the highest E_{pb} (%) (53.33 and 67.83% at particles of 2–5 μm and > 5 μm, respectively) was shown by three minutes after breathing with exercise mode. The more interesting thing is that the E_{pb} (%) was rapidly decreased to a low level according to respiration duration. In particular, the highest E_{pb} (%) (67.83%) of the particles larger than 5 μm was marked at the first three minutes during exercise mode. This result might be caused by the inertial impaction. Inertial impaction affects mainly particles that are larger than 5 μm and refers to the particle's inability to follow sudden change in air flow direction. Here, the sudden change of air flow direction is the turning of aerodynamic flow caused nasal hairs facing the entering air flow. The deviation of the particle from the air streamline increases its probability to deposit on nasal hair (Darquenne, 2012).

Particles with both sizes showed a continuous decrease in E_{pb} (%) with increasing breathing duration with exercise respiration pattern. One of the reasons of this result might be thought that after capturing, the particles gently attached on nasal hairs make their way to the inner wall of nasal passages by the constant breathing.

In general, during exercise, the mouth is more or less continuously open (or oral breathing totally replaces nasal breathing). This means that exercise aggravates the accumulation of particles (at least both middle and large sizes) to higher concentrations in our body even if we breathe through our nose.

3.2 Calculation of Particle Cut-off Efficiency of Different Thickness of Nasal Hairs

It is thought that nasal hair thickness varies with respect to age, sex, and the race. Also, it is expected that nasal hair thickness is crucially important for particle blocking because it plays an important role in capturing particles. In order to make clear the particle cut-off efficiency with respect to nasal hair thickness, a theoretical calculation was performed. Fig. 4 shows how does the nasal hair block particles. Three particle cut-off efficiencies (E), i.e., E by Brownian diffusion ($E_{dif.}$), E by interception ($E_{int.}$), and E by inertial impaction processes ($E_{imp.}$) are fundamental mechanisms for the particle adhesion onto the nasal hair (Becquemin *et al.*, 1991; Gerrity *et al.*, 1979). A more advanced equation for particle cut-off efficiency ($E_{integ.}$) of nasal hairs that integrated three kinds efficiencies as follow:

$$E_{integ.} = 1-(1-E_{dif.})(1-E_{int.})(1-E_{imp.})$$

In this study, the particle cut-off efficiency by inspiration for three kinds of nasal hair thickness (i.e., 50, 75, and 100 μm) was theoretically computed using this integrated $E_{integ.}$ Among the important factors for the integrated $E_{integ.}$, the Renolds number of nasal hairs based on its radius, the Schmidt number of captured particles, the Stokes number of captured particles, the Cunningham slip factor, the particle density, and the Critical stokes number are considered. More details for calculation like variable settings and computation processes were already described in the related articles (Ma *et al.*, 2005; Ma *et al.*, 2004).

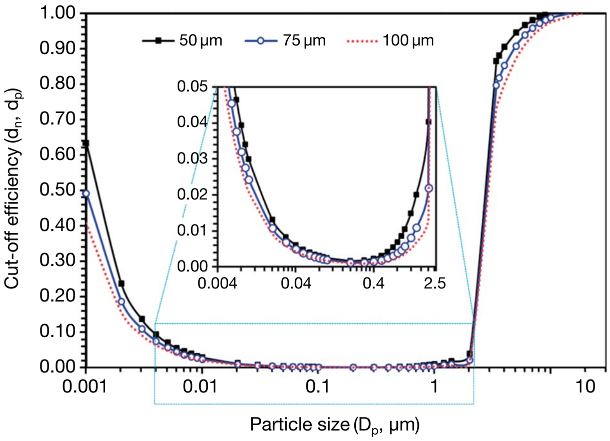

Fig. 5. Particle cut-off efficiency of nasal hairs by inspiration according to particle size and nasal hair thickness.

Fig. 5 shows the $E_{integ.}$ of nasal hairs according to particle size and nasal hair thickness. As one of outstanding features appeared in the $E_{integ.}$ curves, the thinner nasal hair can block particles more efficiently through a whole particle size range. Another peculiarity for the $E_{integ.}$ curves is that it is significantly greater for both nano size and giant size particles. For the particle larger than 2.0 μm, the $E_{integ.}$ increases with increasing particle size because both inertial impaction and interception work more strongly. Meanwhile, for the particles smaller than 0.02 μm in diameter, the $E_{integ.}$ increases with decreasing particle size because of increased Brownian diffusion. It was also found that no meaningful the $E_{integ.}$ at particle size from 0.004 to 0.4 μm for all thickness ranges of nasal hair. This result might be caused by the fact that none of the main mechanisms (i.e., three-kind mechanisms mentioned above) were effective for particle cut-off in this particle size range.

Although this study estimated the $E_{integ.}$ of nasal hairs by only inspiration, according to Wiesmiller *et al.* (2003), the particle deposition fraction in the anterior nasal segment was significantly higher during nose-only breathing (46.0%) compared with nose-in/mouth-out breathing (33.0%). Their study suggested that for inspiration as well as expiration the nasal particle blocking is very efficient and inspiratory efficiency is higher than expiratory.

4. CONCLUSION

According to the results of this study, it can be concluded that nasal hair keeps particles (especially coarse particles) from entering our body. In this study we proved experimentally that nasal breathing would be more advantageous for the particle blocking than oral breathing. Although the particle blocking was clearly shown at the exercise breathing mode, this phenomenon was reduced dramatically after three minutes of exercise. The theoretically calculated particle cut-off efficiency of nasal hairs considering the age- and sex-related changes in nasal hair thickness indicates that the thinner nasal hair can block particles more efficiently through a whole particle size range. Meanwhile, it was also found that no meaningful particle blocking efficiency at particle size from 0.004 to 0.4 μm for all thickness ranges of nasal hair. The reconstructed artificial nasal hairs in the present study is only one of the two kinds of nasal hair. The other kind of nasal hair is referred to as cilia and it is invisible size. Thus, particle blocking by these tiny structures was excluded from our present study. The experimental data in this study obtained by the simplified nasal model were not calibrated exactly by the phenomenon such as a partial variation of the dynamics of nasal air flow in nasal valves. Therefore, in the subsequent further study, the improved nasal model that is closer to the actual nose structure will be introduced. Since it is generally thought that $PM_{2.5}$ is more harmful to health than larger particles (those with an aerodynamic diameter of ≥ 2.5 μm) (Cifuentes *et al.*, 1995), an assessment of fine PM will also be performed in a follow-up study. In addition, the particle blocking efficiency depending on wet condition of nasal hairs will be included.

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