

Nasal Mucociliary Clearance and Sinonasal Symptoms in Healthcare Professionals Wearing FFP3 Respirators: A Prospective Cross-Sectional Study

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Keywords

FFP3 respirator · Mask · Nasal mucociliary clearance · Sinonasal symptom · COVID-19 pandemic

Abstract

Introduction: The purpose of the present study was to assess nasal mucociliary clearance (NMC) and sinonasal symptoms of healthcare professionals wearing filtering facepiece-3 (FFP3) respirators. **Methods:** This prospective cross-sectional study was conducted at a large tertiary care academic center. Thirty-four healthcare professionals working at a coronavirus disease-19 patient care unit were included in the study. Visual analog scale (VAS) scores of sinonasal symptoms (nasal discharge, postnasal discharge, nasal blockage, hyposmia, facial pain/pressure, facial fullness, headache, fatigue, halitosis, cough) and the NMC times of the participants were assessed immediately before wearing FFP3 respirators and after 4 h of work with FFP3 respirators.

Results: The mean age of the participants was 28.82 ± 4.95 (range, 26–31) years. Twenty participants were female and 14 were male. After wearing the FFP3 respirators for 4 h, a statistically significant increase was observed in total VAS scores for all sinonasal symptoms and NMC times ($p < 0.001$). When the VAS score of each sinonasal symptom was evaluated separately, a statistically significant increase was found for VAS scores of nasal discharge, postnasal discharge, nasal

blockage, hyposmia, facial pain/pressure, and facial fullness ($p < 0.05$). **Conclusion:** The present study shows that nasal mucosal functions might be affected significantly after 4 h of using FFP3 respirators. The long-term effects and clinical significance of these short-term changes should be investigated on healthcare professionals in further studies.

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Introduction

The coronavirus disease-19 (COVID-19) pandemic is the most serious global health crisis since the 1917 Spanish flu epidemic. With the COVID-19 outbreak, the importance of respiratory protection for healthcare professionals has been emphasized, and the usage of a filtering facepiece respirator (FFR), which is used to prevent inhalation of toxic and infectious particles in the air, has become important. The World Health Organization recommends using surgical masks to protect against the droplet transmission of severe acute respiratory syndrome coronavirus 2 and FFRs for aerosol-generating procedures [1]. FFRs are more effective than surgical masks because of their ability to filter smaller particles and fit better on the user's face [2]. However, the dead space between the FFR and the face accumulates exhaled carbon dioxide (CO₂), causing it to be inhaled back into the respiratory

tract during the next inspiration [3]. Thus, oxygen (O₂) and CO₂ levels of the air inhaled with FFRs do not meet the working environment standards [4, 5]. CO₂ retention in the FFR dead space has been shown to significantly increase end-tidal CO₂ (EtCO₂) and fractional inspired CO₂ pressure (FiCO₂) [6]. CO₂ levels >3% in the breathing-environment have been associated with some detrimental physiological effects [7]. During the use of FFRs, a short-term negative effect on measures of cardiopulmonary function including increased EtCO₂ and decreased forced expiratory volume and peak power has been found [6, 8]. The long-term effects of these changes are not known. It has also been shown that FFRs cause an increase in face temperature, humidity in the inhaled air, and respiratory resistance [9, 10].

Nasal mucociliary clearance (NMC) is the primary defense mechanism of the respiratory system [11]. Inhaled particles adhere to the nasal mucosa and ciliary activity carries mucus toward the oropharynx [12]. Thus, NMC protects the respiratory system against inhaled particles and microorganisms. Ineffective ciliary activity can lead to acute or chronic infections of the upper and lower respiratory tract [13]. Several studies reported many factors that cause deterioration in NMC [14–16]. Ciliary function may vary due to temperature, pH, osmotic pressure, infections, genetic factors, and iatrogenic factors [17].

We assumed that NMC, which was stated to be affected by many factors in previous studies, may be affected by changes in the inhaled air secondary to the use of filtering facepiece-3 (FFP3) respirators. The aim of the present study was to evaluate the NMC function and sinonasal symptoms of healthcare professionals using FFP3 respirators.

Materials and Methods

Study Design

This was a single-center, prospective, cross-sectional study conducted at the otorhinolaryngology department of a large tertiary care academic center. The study was approved by the Institutional Clinical Research Ethics Committee (approval number: 2021/130) and conducted in accordance with the ethical principles for medical research involving human subjects outlined in the Declaration of Helsinki. Written informed consent was obtained from all participants before their enrollment.

Study Population

Thirty-four healthcare professionals working in the COVID-19 patient care unit and using FFP3 respirators were included in the study. The participants were evaluated through a detailed medical history, otorhinolaryngological examinations, and nasal endoscopy: Those with have a pathology that caused nasal obstruction such as

rhinosinusitis, septum deviation, nasal polyposis, concha bullosa or adenoid hypertrophy; a history of allergy or asthma; a history of upper respiratory tract infection in the last two months; a history of COVID-19; a history of nasal or paranasal sinus surgery; a history of systemic disease, and smokers were excluded from the study.

Outcome Measures

Two visits were conducted after the participants were determined. The first visit was held at 08:00 a.m. before the shifts started, and the second visit was held 4 h later, at 12:00 p.m. during their break. Before the first visit, the participants were accustomed to an indoor environment without an FFR and they were allowed to rest in room air for 30 min. In both visits, sinonasal symptoms (nasal discharge, postnasal discharge, nasal blockage, hyposmia, facial pain/pressure, facial fullness, headache, fatigue, halitosis, cough) were queried using a visual analog scale (VAS) (0 = no complaint, 10 = the worst possible level) and NMC times were measured. Between the two visits, all participants wore the same duck-billed design disposable FFP3 respirator without an exhalation valve (Ege 700 FFP3 NR D; Istanbul, Turkey) provided by the Ministry of Health. We performed a leak check before testing to ensure that the FFR was used as correctly as possible. They worked for 4 h until their break as they did in their routine practice without ever removing the FFR.

Measurement of NMC

NMC times were evaluated by the same otorhinolaryngologist using the sodium saccharin test. The saccharin test was performed according to the method described by Greenstone and Cole [18]. Testing was performed in an area of constant humidity with a room temperature of 20–22°C. Participants were positioned in an upright position. A 1-mm piece of sodium saccharin was placed in the medial side of the inferior nasal turbinate using bayonet forceps. After placing the saccharin particle, subjects were advised not to lean forward or reach out. The participants were asked to avoid deep breathing, talking, coughing, sneezing, blowing their nose, or sniffing during the test. The time interval between the implantation of the particles and detecting the sweet taste in the oropharynx was measured by a timekeeper and was accepted as the NMC time.

Statistical Analysis

The Statistical Package for the Social Sciences (SPSS) for Windows version 22.0 software (SPSS for Windows Inc., Chicago, IL, USA) was used for the statistical analyses. The suitability of the quantitative data for normal distribution was tested using the Shapiro-Wilk test. Categorical characteristics were described using frequency and proportions. Continuous outcomes were described as means (standard deviation) or median (first [Q1] and third quartiles [Q3]) and compared with either the paired-samples *t* test or the Wilcoxon's signed-rank test, depending on normality. Correlation analysis was performed using Spearman's correlation test. Statistical significance was accepted as $p < 0.05$.

Results

This prospective study included 34 healthcare professionals. The average age of the participants was 28.82 ± 4.95 (range, 26–31) years. Twenty subjects (58.8%) were female and 14 (41.2%) were male.

Table 1. The NMC times and total VAS scores of all sinonasal symptoms at baseline and after the FFR visits

	Baseline	After the FFR	<i>p</i> value
NMC time, min			
Median (Q1–Q3)	6.00 (5.00–9.00)	11.50 (9.0–15.00)	<0.001*
Mean ± SD	6.97±2.52	13.00±5.42	
VAS			
Median (Q1–Q3)	7.50 (1.75–15.25)	10.50 (4.25–20.25)	<0.001*
Mean ± SD	9.20±8.24	13.00±10.85	

FFR, filtering facepiece respirator; NMC, nasal mucociliary clearance; VAS, visual analog scale. Wilcoxon signed rank test, * *p* < 0.001.

Table 2. The VAS score of each sinonasal symptom at baseline and after the FFR visits

Sinonasal symptoms	Baseline	After the FFR	<i>p</i> value
Nasal discharge			
Median (Q1–Q3)	0.00 (0.00–2.00)	1.50 (0.00–3.25)	0.007*
Mean ± SD	1.02±1.40	2.14±2.65	
Postnasal discharge			
Median (Q1–Q3)	1.00 (0.00–3.00)	2.00 (0.00–4.00)	0.010*
Mean ± SD	1.79±2.34	2.58±2.60	
Nasal blockage			
Median (Q1–Q3)	0.50 (0.00–2.00)	1.50 (0.00–2.00)	0.015*
Mean ± SD	1.20±1.75	1.73±2.15	
Hyposmia			
Median (Q1–Q3)	0.00 (0.00–0.25)	0.00 (0.00–1.00)	0.023*
Mean ± SD	0.67±1.42	0.91±1.71	
Facial pain/pressure			
Median (Q1–Q3)	0.00 (0.00–0.00)	0.00 (0.00–1.00)	0.010*
Mean ± SD	0.08±0.37	0.52±1.05	
Facial fullness			
Median (Q1–Q3)	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0.038*
Mean ± SD	0.14±0.43	0.35±0.73	
Headache			
Median (Q1–Q3)	0.00 (0.00–1.00)	0.00 (0.00–2.00)	0.199
Mean ± SD	0.73±1.35	1.02±1.83	
Fatigue			
Median (Q1–Q3)	1.00 (0.00–3.00)	1.50 (0.00–6.00)	0.063
Mean ± SD	1.97±2.44	2.52±2.95	
Halitosis			
Median (Q1–Q3)	0.00 (0.00–2.00)	0.00 (0.00–1.25)	0.655
Mean ± SD	0.91±1.58	0.97±1.71	
Cough			
Median (Q1–Q3)	0.00 (0.00–0.00)	0.00 (0.00–0.00)	1.000
Mean ± SD	0.38±0.98	0.38±0.92	

FFR, filtering facepiece respirator; VAS, visual analog scale. Wilcoxon signed rank test, * *p* < 0.05.

The median NMC times measured at baseline and after the FFR visits were 6 and 11.5 min, respectively. After wearing the FFP3 respirator for 4 h, a statistically significant increase was observed in the NMC time (*p* < 0.001) (Table 1).

The median total VAS scores of all sinonasal symptoms at baseline and after the FFR visits were 7.5 and 10.5, respectively. After wearing the FFP3 respirator for 4 h, a statistically significant increase was observed in the total VAS scores for all sinonasal symptoms (*p* < 0.001) (Table 1). When the VAS score of each sinonasal symptom

was evaluated separately, a statistically significant increase was found for VAS scores of nasal discharge, postnasal discharge, nasal blockage, hyposmia, facial pain/pressure, and facial fullness ($p < 0.05$) (Table 2). It was noteworthy that there was an increase in other sinonasal symptoms, except for cough (Table 2).

Spearman's correlation analysis showed no correlation between the change in the NMC time and the change in total VAS scores of all sinonasal symptoms ($r = 0.073$, $p = 0.681$). There was no correlation between the change in the NMC time and the change in the VAS score of each sinonasal symptom ($p > 0.05$).

Discussion

The present study evaluated the effect of short-term FFP3 respirator use on NMC and sinonasal symptoms in healthcare professionals. The NMC time measurements and sinonasal symptoms were found to be increased significantly according to baseline values. A statistically significant increase was found for VAS scores of nasal discharge, postnasal discharge, nasal blockage, hyposmia, facial pain/pressure, and facial fullness.

Despite their widespread use, few reports have been published on the physiological effects of FFRs on healthcare professionals. A significant increase in heart rate, respiratory rate, and blood pressure has been reported during moderate-to-heavy exertion performed with FFRs compared with exertion without a mask [19]. A recent study reported a significant alteration in ocular vascular structures after wearing FFP3 respirators for 4 h in healthcare professionals [20]. Another study reported that, in healthy individuals, ventilation, cardiopulmonary exercise capacity, and comfort were decreased with surgical masks and substantially deteriorated with the use of FFRs [8]. Another recent report showed that the use of FFP2 respirators by healthcare professionals significantly increased EtCO₂ and FiCO₂ pressure values [6]. There are also reports indicating no significant physiological change after 1 h of mild-to-moderate effort with FFRs [4, 6, 8, 19, 21, 22]. However, in these studies, participants were only tested for 1 h of exercise at a low-to-moderate workout rate under laboratory conditions. Our study was conducted under the real working conditions of healthcare professionals.

The NMC system, which is responsible for cleaning inhaled particles and pathogens, is the most important defense mechanism of the airway [23]. Some genetic disorders or environmental and microbial toxins may affect

NMC [24]. Recent studies have investigated the effects of various factors on NMC. One of these studies reported that hypothyroidism led to prolonged NMC times [25]. In another recent study, NMC time was found to be longer in patients with multiple sclerosis [26]. That NMC was affected by external factors was reported in a study conducted on wood industry workers [27]. Koparal et al. [28] reported prolonged NMC times in patients with COVID-19.

There are different opinions in the literature about whether mucociliary activity is affected by effort. Studies suggest that mucociliary clearance is significantly increased during exercise [29, 30]. Another study reported that simple exercises such as performing routine tasks in a hospital setting did not affect on mucociliary clearance [31]. It is difficult to evaluate the results of the present study in terms of the effort effect because, unlike these studies, the participants were working with FFP3 respirators in the present study.

In the literature, it is mentioned that FFRs cause CO₂ retention, temperature increase, and a humidity increase in the inhaled air. The dead space between the FFR and the face accumulates exhaled CO₂, causing it to be inhaled back into the respiratory tract during the next inspiration [3]. Thus, the O₂ and CO₂ levels of the air inhaled with FFRs do not meet the working environment standards [4, 5]. CO₂ retention in the FFR dead space has been shown to significantly increase EtCO₂ and FiCO₂ [6]. A breathing environment containing CO₂ >3% has been associated with some detrimental physiological effects [7]. It has also been shown that FFRs cause an increase in face temperature, humidity in the inhaled air, and respiratory resistance [9, 10]. Ciliary function may vary due to temperature, pH, osmotic pressure, infections, genetic factors, and iatrogenic factors [17]. We did not measure the temperature, CO₂ levels, and humidity of the air remaining in the FFR dead space. However, we think CO₂ retention may be existed in the FFR dead space due to the FFRs used in this study had no exhalation valves. We speculated that prolonged NMC times in the present study would result from CO₂ retention, increased temperature, and humidity caused by 4 h of work with FFP3 respirators. It may be more enlightening to examine the temperature, CO₂ levels, and humidity of the air remaining in the FFR dead space in detail in further studies.

Ciliary beat frequency can vary depending on the temperature [32, 33]. Several studies investigated the effect of temperature on mucociliary clearance and most showed that a decrease in temperature altered it negatively [32, 34–36]. The ciliary beat frequency of the trachea was

shown not to be influenced by the fluid with pH values of 7–10 in an animal study but decreased with higher and lower values [37]. Under low relative humidity conditions, insensible water loss increases, and mucociliary clearance is delayed [38]. We did not measure the temperature, pH, and humidity of the air remaining in the FFR dead space. However, we think it may have an acidic pH due to CO₂ retention. It may be more enlightening to examine the air temperature in the FFR dead space in detail in further studies.

Kirtsreesakul et al. [39] reported a positive correlation between NMC times and nasal symptom scores. There was no correlation between NMC times and sinonasal symptoms in the present study.

The main limitation of the present study was that there was no control group working in the same environment without wearing an FFR. Due to the risk of COVID-19 transmission, a control group with these features could not be formed. Also, we did not measure the temperature, CO₂ levels, and humidity of the air remaining in the FFR dead space. In addition, due to mandatory needs, the uninterrupted wearing time of the FFP3 respirator was limited to 4 h. Another limitation was the small size of the subject population, which may limit the generalizability of the findings. Further studies with a larger number of participants are needed to confirm the results.

Conclusion

In conclusion, we report a significant increase in NMC times and sinonasal symptoms after wearing FFP3 respirators for 4 h in healthcare professionals. Considering the ongoing COVID-19 pandemic, healthcare professionals will have to work with these respirators for a long time. More studies are needed on the effects and safety of FFRs on healthcare professionals' nasal mucosal physiology in

strenuous physical and occupational activities. Further studies reporting long-term results will provide beneficial knowledge in later days.

Statement of Ethics

The study was approved by the Haydarpaşa Numune Training and Research Hospital Clinical Research Ethics Committee (approval number: 2021/130) and conducted in accordance with the ethical principles for medical research involving human subjects outlined in the Declaration of Helsinki. Written informed consent was obtained from all participants before their enrollment.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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Author Contributions

Selçuk Yıldız, Aykut Yankuncu, and Çiğdem Tepe Karaca contributed to study conception and design, acquisition of data, analysis and interpretation of data, drafting the article and revisions, and final approval of the article. Sema Zer Toros contributed to study conception and design, analysis and interpretation of data, drafting the article and revisions, and final approval of the article.

Data Availability Statement

The data that support the findings of this study are not publicly available due to their containing information that could compromise the privacy of research participants but are available from the corresponding author upon reasonable requests.

References

- 1 World Health Organization. Rational use of personal protective equipment for coronavirus disease (COVID-19) and considerations during severe shortages: interim guidance 2020. 2020 [cited 2020 Apr 6]. Available from: <https://apps.who.int/iris/handle/10665/331695>.
- 2 Chu DK, Akl EA, Duda S, Solo K, Yaacoub S, Schünemann HJ, et al. Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. *Lancet*. 2020;395(10242):1973–87.
- 3 Caretti D, Coyne KM. Unmanned assessment of respirator carbon dioxide levels: comparison of methods of measurement. *J Occup Environ Hyg*. 2008;5(5):305–12.
- 4 Roberge RJ, Coca A, Williams WJ, Powell JB, Palmiero AJ. Physiological impact of the N95 filtering facepiece respirator on healthcare workers. *Respir Care*. 2010;55(5):569–77.
- 5 Roberge RJ, Coca A, Williams WJ, Palmiero AJ, Powell JB. Surgical mask placement over N95 filtering facepiece respirators: physiological effects on healthcare workers. *Respirology*. 2010;15(3):516–21.
- 6 Özdemir L, Azizoğlu M, Yapıcı D. Respirators used by healthcare workers due to the COVID-19 outbreak increase end-tidal carbon dioxide and fractional inspired carbon dioxide pressure. *J Clin Anesth*. 2020;66:109901.

- 7 Khaw KS, Kee WDN, Tam YH, Wong MK, Lee SWY. Survey and evaluation of modified oxygen delivery devices used for suspected severe acute respiratory syndrome and other high-risk patients in Hong Kong. *Hong Kong Med J*. 2008;14(5 Suppl):27–31.
- 8 Fikenzler S, Uhe T, Lavall D, Rudolph U, Falz R, Busse M, et al. Effects of surgical and FFP2/ N95 face masks on cardiopulmonary exercise capacity. *Clin Res Cardiol*. 2020;109(12): 1522–30.
- 9 Scarano A, Inchingolo F, Lorusso F. Facial skin temperature and discomfort when wearing protective face masks: thermal infrared imaging evaluation and hands moving the mask. *Int J Environ Res Public Health*. 2020; 17(13):4624.
- 10 Harber P, Beck J, Brown C, Luo J. Physiologic and subjective effects of respirator mask type. *Am Ind Hyg Assoc J*. 1991;52(9):357–62.
- 11 Duran M, Ulkü CH. Effect of radiofrequency thermal ablation treatment on nasal mucociliary clearance in patients with isolated inferior turbinate hypertrophy. *Kulak Burun Bogaz Ihtis Derg*. 2014;24(4):185–9.
- 12 Jones N. The nose and paranasal sinuses physiology and anatomy. *Adv Drug Deliv Rev*. 2001;51(1–3):5–19.
- 13 Kesimci E, Bercin S, Kutluhan A, Ural A, Yamanturk B, Kanbak O. Volatile anesthetics and mucociliary clearance. *Minerva Anesthesiol*. 2008;74(4):107–11.
- 14 Kucur C, Ozbay I, Gulcan E, Kulekci S, Aksoy S, Oghan F. Evaluation of nasal mucociliary activity in patients with chronic renal failure. *Eur Arch Otorhinolaryngol*. 2016;273(5): 1167–71.
- 15 Soyulu Özler G, Akbay E, Akkoca AN, Karapınar OS, Şimşek GÖ. Does menopause effect nasal mucociliary clearance time? *Eur Arch Otorhinolaryngol*. 2015;272(2):363–6.
- 16 Uysal IO, Gökakın AK, Karakuş CF, Devenci K, Hasbek Z, Sancakdar E. Evaluation of nasal mucociliary activity in iatrogenic hypothyroidism. *Eur Arch Otorhinolaryngol*. 2013; 270(12):3075–8.
- 17 Houtmeyers E, Gosselink R, Gayan-Ramirez G, Decramer M. Regulation of mucociliary clearance in health and disease. *Eur Respir J*. 1999;13:1177–88.
- 18 Greenstone M, Cole PJ. Ciliary function in health and disease. *Br J Dis Chest*. 1985;79(1): 9–26.
- 19 Jones JG. The physiological cost of wearing a disposable respirator. *Am Ind Hyg Assoc J*. 1991;52(6):219–25.
- 20 Yildiz MB, Balci S, Özçelik Köse A, Yenerel NM, Yildiz HE. Retinal and choroidal vascularity changes in healthcare professionals wearing FFP3 respirators. *Cutan Ocul Toxicol*. 2021;40(2):70–7.
- 21 Kim JH, Wu T, Powell JB, Roberge RJ. Physiologic and fit factor profiles of N95 and P100 filtering facepiece respirators for use in hot, humid environments. *Am J Infect Control*. 2016;44(2):194–8.
- 22 Kao TW, Huang KC, Huang YL, Tsai TJ, Hsieh BS, Wu MS. The physiological impact of wearing an N95 mask during hemodialysis as a precaution against SARS in patients with end-stage renal disease. *J Formos Med Assoc*. 2004;103(8):624–8.
- 23 Stevens WW, Lee RJ, Schleimer RP, Cohen NA. Chronic rhinosinusitis pathogenesis. *J Allergy Clin Immunol*. 2015;136(6):1442–53.
- 24 Gudis D, Zhao KQ, Cohen NA. Acquired cilia dysfunction in chronic rhinosinusitis. *Am J Rhinol Allergy*. 2012;26(1):1–6.
- 25 Kulekci Ozturk S, Sakci E, Kavvasoglu C. Rhinitis in patients with acquired hypothyroidism. *Eur Arch Otorhinolaryngol*. 2021;278(1): 87–92.
- 26 Sahin E, Hamamcı M, Kantekin Y. Measurement of mucociliary clearance in the patients with multiple sclerosis. *Eur Arch Otorhinolaryngol*. 2020;277(2):469–73.
- 27 Özler GS, Akoğlu E. Impairment of nasal mucociliary clearance time in wood industry workers. *Eur Arch Otorhinolaryngol*. 2020; 277(2):493–6.
- 28 Koparal M, Kurt E, Altuntas EE, Dogan F. Assessment of mucociliary clearance as an indicator of nasal function in patients with COVID-19: a Cross-Sectional Study. *Eur Arch Otorhinolaryngol*. 2021;278(6):1863–8.
- 29 Oldenburg FA, Dolovich MB, Montgomery JM, Newhouse MT. Effects of postural drainage, exercise, and cough on mucus clearance in chronic bronchitis. *Am Rev Respir Dis*. 1979;120:739–45.
- 30 Wolff RK, Dolovich MB, Obminski G, Newhouse MT. Effects of exercise and eucapnic hyperventilation on bronchial clearance in man. *J Appl Physiol Respir Environ Exerc Physiol*. 1977;43:46–50.
- 31 Clarke SW, Pavia D, editors. *Aerosols and the lung: clinical and experimental aspects*. London: Butterworth; 1984.
- 32 Green A, Smallman LA, Logan AC, Drake-Lee AB. The effect of temperature on nasal ciliary beat frequency. *Clin Otolaryngol Allied Sci*. 1995;20(2):178–80.
- 33 Ingels KJ, Kortmann MJ, Nijziel MR, Graamans K, Huizing EH. Factors influencing ciliary beat measurements. *Rhinology*. 1991; 29(1):17–26.
- 34 Kilgour E, Rankin N, Ryan S, Pack R. Mucociliary function deteriorates in the clinical range of inspired air temperature and humidity. *Intensive Care Med*. 2004;30(7):1491–4.
- 35 Diesel DA, Lebel JL, Tucker A. Pulmonary particle deposition and airway mucociliary clearance in cold-exposed calves. *Am J Vet Res*. 1991;52(10):1665–71.
- 36 Mwimbi XK, Muimo R, Green MW, Mehta A. Making human nasal cilia beat in the cold: a real time assay for cell signalling. *Cell Signal*. 2003;15(4):395–402.
- 37 van de Donk HJ, Zuidema J, Merkus FW. The influence of the pH and osmotic pressure upon tracheal ciliary beat frequency as determined with a new photo-electric registration device. *Rhinology*. 1980;18:93–104.
- 38 Sunwoo Y, Chou C, Takeshita J, Murakami M, Tochihara Y. Physiological and subjective responses to low relative humidity. *J Physiol Anthropol*. 2006;25:7–14.
- 39 Kirtsreesakul V, Somjareonwattana P, Rutanaphol S. The correlation between nasal symptom and mucociliary clearance in allergic rhinitis. *Laryngoscope*. 2009;119(8):1458–62.