Evaluation on Masks with Exhaust Valves and with Exhaust Holes from 
Physiological and Subjective Responses

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Abstract The purpose of this study was to compare the effects of wearing different kinds of masks on the ear canal temperature, heart rate, clothing microclimate, and subjective perception of discomfort. Ten subjects performed intermittent exercise on a treadmill while wearing the protective masks in a climatic chamber controlled at an air temperature of 25°C and a relative humidity of 70%. Two types of mask—mask A, with exhaust valves and mask B, with exhaust holes—were used in the study. The results of this study indicated: (1) The subjects had a tendency toward lower maximum heart rate when wearing mask A than when wearing mask B. (2) Temperatures and absolute humidities (the outer surface of mask, the microclimate inside the mask, the chest wall skin and microclimate) of mask A were significantly lower than those of mask B. (3) The ear canal temperature increased significantly in mask B as compared to that in mask A. (4) The ear canal temperature showed significant augmentation along with increased temperature and humidity inside the mask microclimate. The mask microclimate temperature also affected significantly the chest microclimate temperature. (5) Mask A was rated significantly lower for perception of humidity, heat, breath resistance, tightness, unfitness, odor, fatigue, and offered less overall discomfort than mask B. (6) Subjective preference for mask A was higher. (7) The ratings of subjective overall discomfort showed significant augmentation along with increased wetness and fatigue. We discuss how the ventilation properties of masks A and B induce significantly different temperature and humidity in the microclimates of the masks and the heat loss of the body, which have profound influences on heart rate, thermal stress, and subjective perception of discomfort. J Physiol Anthropol 27(2): 93–102, 2008 http://www.jstage.jst.go.jp/browse/jpa2 [DOI: 10.2214/jpa2.27.93]

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Introduction

Masks are required in many tasks. For example, workers in the chemical industry, miners, and farmers use masks to prevent inhalation of toxic or fibrogenic agents, and health care workers use masks as protection against microbes such as tubercular bacilli and SARS-associated coronaviruses (SARS-CoV). A case-control study in five Hong Kong hospitals during the SARS outbreak suggests that the mask was essential for protection, since only this measure was significantly better than wearing gloves or gowns, or washing the hands (Seto et al., 2003). Despite their protective value, the masks are used in only 20% to 30% of the work situations in which they are needed (Aucoin, 1975; Vihma, 1981). The failure to wear them may be due to various sensations of discomfort, many studies having shown a variety of physiological effects associated with their use. In general, the research has shown changes associated with increased effort of resistance to breathing due to increased dead air space, increased thermal stress and a variety of cardiovascular stresses (Harper et al., 1989; White et al., 1991; Nielsen et al., 1987; Jones, 1991; Hayashi and Tokura, 2004). According to Nielsen et al. (1987), the acceptability of both the ambient thermal environment and of the thermal microclimate in the masks was primarily determined by the ambient air temperature, but it was influenced also by the clothing microclimate temperature and humidity inside the mask. Our previous study found that when subjects wore masks (N95 and surgical masks) and exercised on the treadmill, their heart rate and the microclimate temperature and humidity inside the mask increased with the duration of exercise and the workload. Also, subjective ratings of humidity, hotness, breath resistance, and overall discomfort increased gradually with the duration of exercise and the workload (Li et al., 2005).

Hayashi and Tokura (2004) found that, in order to reduce heat stress of the body when the farmers were spraying pesticide in a warm environment, it was important to prevent
an excessive increase of microclimate temperature and humidity inside the mask. They found that a mask with an exhaust valve was effective in reducing temperature and humidity inside the mask when two kinds of mask (with and without exhaust valve) were compared. However, a comparison of the effects of masks with exhaust valves and exhaust holes on microclimate temperature and humidity inside the mask has never been made.

In this paper, we report an experimental study on the effects of wearing different kinds of masks (with exhaust valves and exhaust holes) on the ear canal temperature, heart rate, clothing microclimates (temperature and humidity), and perception of discomfort. The purpose of the study was to investigate whether mask A, with exhaust valves, and mask B, with exhaust holes, differed in their effects in reducing heat stress and perception of discomfort of persons exercising and resting in a warm environment.

Materials and Method

Subjects

Ten healthy 23- to 39-yr-old subjects, five males and five females, were recruited for this experiment. The physical characteristics (mean±SD) were 32.4±6.4 years for age, 171.4±4.2 cm for height, 70±12.4 kg for body mass, and 1.78±0.15 m² for body surface area in the male subjects, and 28.2±4.1 years for age, 163.8±5.1 cm for height, 52.9±7.0 kg for body mass, and 1.52±0.12 m² for body surface area in the female subjects.

None of the subjects was smokers. For female subjects, studies were commenced only during their follicular phases. Each subject participated twice in the experiment, at the same time of day and wearing one of the two types of mask on each occasion. Informed consent was obtained from each of the volunteers. The Human Subjects Ethics and Sub-Committee of The Hong Kong Polytechnic University approved the experimental protocol.

Masks

Figure 1 illustrates the two types of mask used in this experiment. Mask A was made of laminated polypropylene with polyester fabrics with two exhaust valves made of plastic and situated at its back. The exhalation valves open to release exhaled air and close during inhalation. The inhalation valves perform in the opposite way, opening during inhalation and closing during exhalation. Fresh air enters into the mask through two inhalation valves covered by a filter that is made from the same fabric as a surgical mask to prevent microbes or other toxic substances entering the respiratory tract by inhalation. Mask B was also made of laminated polypropylene with polyester fabrics and had two exhaust holes situated at its back. The weathers inhaled and exhaled through the same two exhaust holes covered by filter materials, which was also made from the same fabric as a surgical mask. The major difference between Masks A and B was that the former had exhaust valves, but the latter did not.

Measurements

Clothing microclimates (temperature, humidity) inside and outside the mask, between the chest wall and shirt/blouse, as well as chest skin temperatures were measured by thermistors (accuracy±0.1°C) and humidity sensors (accuracy±3% rh) and recorded continuously by a logger (SCXI-1161, National Instruments, U.S.A) every 30 s for 70 min. Chest microclimates (temperature, humidity) and chest skin temperature were measured from the left and right chest regions. Mask microclimates (temperature, humidity) inside the mask were measured from the right cheek. The temperature and humidity outside the mask surface were also measured above the right cheek. Ear canal temperature was measured continuously by a temperature sensor “LT-ST 08-00” (Gram, Japan, accuracy±0.1°C) inserted deep into the ear canal of the left ear and stored in the data logger LT-8A (Nikkiso-YSI, Japan) every 30 s for 70 min, and then sampled by a computer through an A-D converter. Heart rate was measured every min by a Polar Heart Rate Receiver (810i™) worn on the subject’s left wrist, and an electrode for a Polar Heart Rate Monitor was fastened to the subject’s chest (Polar Electro, U.S.A). Blood pressure was measured, at 30, 50, 60, 70, 80, 90, and 100 minutes, with an Upper Arm Blood Pressure Meter (EW 3100, BMEW Ltd. Beijing). Prior to the study each subject underwent the Polar Fitness Test on a motor-driven treadmill to estimate individual maximal aerobic power and to get predicted maximum heart rate value using a Polar Heart Rate Monitor (810i™).

Perception of discomfort

Subjects were required to rate their perceptions on ten aspects of discomfort: humidity, hotness, breathing resistance,
itchiness, tightness, saltiness, unfit, odor, fatigue and overall discomfort, after wearing the mask for 30, 50, 60, 70, 80, 90, and 100 minutes. The scales for each sensation are listed in Table 1. These scales ranged from 0 to 10, with “0” representing “not at all” or “comfortable”, “5” representing “mildly” or “uncomfortable” and “10” representing the “strongly” or “extremely uncomfortable”. In addition, after wearing the mask for 100 min, the subjects were asked “how do you like the mask?” The scales are also listed in Table 1. The scales ranged from 0 to 10, with “0” representing “not at all”, “5” representing “acceptable” and “10” representing the “very fond of”. This rating was used to obtain the preference of subjects for the two kinds of masks. The subjects were also asked whether they found mist on their glasses and when mist began while wearing the glasses.

**Experimental protocol**

A rigid procedure was followed to standardize the initial heat content of the experimental masks, thus eliminating this as a factor of variation for the heat exchange in the body-mask environment during the experiment. The masks were stored in the experimental laboratory ($T_{a}$ of 23±3°C, rh of 64±4%) for at least two hours before the experimental procedure began. The experiments were carried out twice a day. The order of the experiments was randomized for the participants, and for the types of masks. Any individual always performed the two parts of the experiment at the same time of two different days. The participant entered a climatic chamber, controlled at an air temperature of 25°C and a relative humidity of 70%, which was similar to the conditions at the hospitals where health care workers worked. After the body mass had been measured, the participant wore a 100% cotton T-shirt, short pants and sports sandals. The sensors were attached (for sites, see above) with adhesive surgical tape. Before commencement of the exercises, the participants sat in a chair for 30 minutes (R0), during which the participant was asked to drink 500 ml water, he/she then put on the randomly selected mask. The participant then walked for 20 minutes on a treadmill at a level walking speed of 3.2 km/hr (E1), rested for 10 minutes (R1), walked for 10 minutes at 4.8 km/hr (E2), rested for 10 minutes (R2), and finally walked for 10 minutes at 6.4 km/hr (E3), and rested for 10 minutes (R3). The workloads at a level walking speed of 4 km/hr represented approximately 23% of maximum work capacity for the subjects while not wearing protective clothing (calculated, based on the initial maximal exercise tests) (White et al., 1991). The participant took off the mask after 100 minutes, at the end of the experimental schedule.

**Statistical analysis**

The average patterns of blood pressure, skin and clothing microclimates (temperature and humidity), ear canal temperature, and various subjective sensations were analyzed by a two-factor analysis of variance with repeated measures (the main effects were type of clothing and time of the experiment). In the event that an ANOVA revealed a significant main effect, the Bonferroni multiple tests were used for a post-hoc test to locate significant differences between means during the experimental period. The statistical significances of the differences on the mean average and maximum heart rates between the two types of masks were assessed using a paired-samples t-test.

Multiple linear regression analyses (stepwise regression) were used to illustrate the relationship between the ear canal temperature, chest microclimate temperature and temperature and humidity inside the mask microclimate, and to predict the factors affecting the subjective overall discomfort using all subjective observations. All differences reported were significant at the $p<0.05$ level, while differences with $0.05<p<0.1$ will be referred to as a tendency in the data.

**Results**

**Heart rate and blood pressure**

Figure 2 shows the mean average and maximum heart rates when ten subjects wore masks A and B. The mean average heart rate was not significantly different for the two types of masks. The overall maximum heart rates (beats/min)±SD were 127.9±19.7 and 141±13.9 in masks A and B, respectively. There was a tendency that subjects had a higher maximum heart rate wearing mask B compared with wearing masks A ($t$=2.08, $df$=8, $p$=0.07). Systolic and diastolic blood pressures were not significantly different wearing two kinds of masks.

| The perceptions | The ratings | The perception of overall discomfort | The perceptions | The ratings | "How do you like the mask?" | "(Subjective preference)"
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**Table 1** Scale of measuring subjective perceptions
Evaluation on Masks with Exhaust Valves and with Exhaust Holes from Physiological and Subjective Responses

Fig. 2  Average and maximum heart rates under the influence of the two kinds of masks.
The values are means ± SEM (n = 10).

Temperatures and humidities
Microclimate temperatures
Figure 3 shows temporal changes in temperatures at the outer surface of the mask (A), in the microclimate inside the mask (B), the microclimate between chest wall skin and clothing (C), and of the chest wall skin (D). The mean outer surface temperature of mask B was significantly higher than those of mask A (F = 22.75, p < 0.001). The microclimate temperature inside the mask was significantly higher with mask B than with mask A (F = 106.5, p < 0.001). The mean chest wall microclimate temperature tended lower when mask A was worn compared with when mask B was worn (F = 3.55, p = 0.06), and the chest wall skin temperature was significantly lower when mask A was worn compared with mask B (F = 10.71, p = 0.001).

Ear canal temperature
Figure 4 shows temporal change in mean ear canal temperature from the initial level (the end of the R0) under the influence of the two kinds of masks. A significant increase of canal temperature was observed with mask B. The canal temperature only increased slightly or even decreased slightly during E1 and R3 with mask A. The mean ear temperature increase was significantly higher when mask B was worn compared with when mask A was worn (F = 121.21, p < 0.001).

Microclimate humidities
Figure 5 shows temporal changes in absolute humidities at the outer surface of the masks (A), the microclimates inside the masks (B), the microclimates between the chest wall skin and clothing (C), and the chest wall skin (D). The absolute humidities increased gradually with time and increase of workload as a whole and the peak was located on the third exercise-rest periods, except for an initial fall from R0 to R1 in the outer surface of the masks. Chest wall microclimate and chest wall skin absolute humidities significantly increased from R2 periods when the subjects wore masks A and B. The mean outer surface absolute humidity of the mask B was significantly higher than that of mask A (F = 6.85, p < 0.01). Figure 5B showed that the absolute microclimate humidity inside mask A was significantly lower than inside mask B. The overall mean absolute humidity ± SEM inside the masks were 26.17 ± 0.08 and 27.50 ± 0.07 for masks A and B respectively. The mean chest wall microclimate humidity tended lower when mask A was worn compared with when mask B was worn (F = 3.61, p = 0.058), and the chest wall skin humidity was significantly lower with mask A compared with mask B (F = 118.85, p < 0.001).

Relationship between the ear canal temperature, chest microclimate temperature, and temperature and humidity inside the mask microclimate
Multiple linear regressions including the temperature (T_{mask micro}) and humidity (H_{mask micro}) inside the mask microclimate as independent variables, and the ear canal temperature (T_{ear}) and chest microclimate temperature (T_{chest micro}) as dependent variables, gave:

\[ T_{ear} = 27.996 + 0.161 T_{mask micro} + 0.718 H_{mask micro} \]
\[ R^2 = 0.728, \text{ Adjusted } R^2 = 0.726, F = 371.34, \text{ df} = 277, p < 0.001 \] (1)

The ear canal temperature showed significant augmentation along with increased temperature and humidity inside the mask microclimate, in which the humidity was a more important determinant.

\[ T_{chest micro} = 13.555 + 1.181 T_{mask micro} - 0.896 H_{mask micro} \]
\[ R^2 = 0.702, \text{ Adjusted } R^2 = 0.493, F = 134.838, \text{ df} = 277, p < 0.001 \] (2)

Chest microclimate temperature showed significant augmentation along with increased temperature and decreased humidity inside the mask microclimate, in which the temperature was a more important determinant.

Subjective ratings
Figure 6 compares subjective ratings for humidity, hotness, breath resistance, and overall discomfort for the two types of masks. In general, the ratings of the sensations increased gradually with the duration of exercise and the workload. Humid (F = 11.58, p < 0.001), hot (F = 13.11, p < 0.001), breath resistance (F = 4.96, p < 0.001), and overall discomfort (F = 18.88, p < 0.001) were significantly higher in the E3 periods than in the rest periods and E1. Mask A had significantly lower ratings than Mask B, which suggested that when wearing Mask A, the subject felt drier (F = 11.02, p <
Fig. 3 Temporal change in mean temperature outside (A), inside (B), in the chest wall microclimate (C), and in chest wall skin (D) of the two kinds of masks. The values are means of each rest and exercise period±SEM (n=10). For definitions of E1, E2, E3 and R1, R2, R3, see Methods.

Fig. 4 Temporal change in mean ear canal temperature from the initial level (the end of the R0) under the influence of the two kinds of masks. The values are means of each rest and exercise period temperature change±SEM (n=8). For definitions of E1, E2, E3 and R1, R2, R3, see Methods.

0.001), cooler (F=12.37, p<0.001), more able to breathe easily (F=19.62, p<0.001), and felt less uncomfortable (F=3.27, p=0.075) than when wearing Mask B.

Figure 7 shows the subjective ratings for other sensations obtained while the subjects were wearing the masks. During the E3 periods the subjective perceptions feeling itchy (F=2.57, p<0.05) or fatigued (F=17.79, p<0.001) were significantly higher than all rest periods and E1. The ratings for the subjective perceptions feeling tight, unfit, odorous and fatigued were significantly lower when the subjects were wearing Mask A than when they were wearing Mask B, which suggested that the subjects felt less unfit (F=8.94, p<0.01), less tight (F=38.18, p<0.001), less odorous (F=4.17, p<0.05) and less fatigued (F=3.99, p<0.05) with Mask A than with Mask B.

Moreover, for the subjects wearing glasses, wearing mask A was rated as producing significantly less mist over the glasses than wearing mask B (F=6.61, p<0.05). However, there were no significant differences regarding the time that the mist began when the subjects were wearing both Masks A and B.

Figure 8 shows the preferences of subjects for the two types of masks. Subjective preference for the Mask A was
significantly higher than for the Mask B ($F=7.75$, $p<0.01$), indicating that mask A was significantly more acceptable to the subjects.

A multiple linear regression including all subjective sensations as independent variables on overall discomfort (OD) as a dependent variable, gave the following equation:

$$OD = 0.491 + 0.715 W + 0.419 F - 0.467 R$$

$$R = 0.910, R^2 = 0.828; F = 38.437, df = 24, p < 0.001$$  (3)

The equation revealed that perceived wetness (W), fatigue (F), and breath resistance (R) significantly influenced perceived overall discomfort when the masks were worn. The ratings of subjective overall discomfort showed significant augmentation along with increased wetness and fatigue. Of them all, the subjective perception of feeling humid was the most important factor affecting perceived overall discomfort.

**Discussion**

In this study, the increases in ear canal temperature, mask and clothing microclimates (temperature and humidity), chest skin temperature and humidity, heart rate and more ratings in the subjective perceptions for humidity, heat, breath resistance, overall discomfort and other sensations when wearing the mask B suggest that this mask poses substantial additional stress to the wearer.

The present results have shown that the microclimate temperature and humidity inside the mask were kept significantly lower throughout the whole experimental period when wearing mask A rather than mask B (Figs. 3B and 5B), suggesting that the ventilation between the air inside the mask and outside air occurred more efficiently with mask A than with mask B.

Many studies have reported that the processes of evaporation and heat dissipation through clothing depend on the properties and design of the clothing, on the body movements and on the environmental conditions (Holmer, 1985; Nielsen et al., 1989). Similarly, the design of the masks may also influence heat dissipation through masks. Both masks A and B used in this study have differences in design. Mask A has two valves, the exhalation valves closing when air is inhaled and opening when air is exhaled. The inhalation valves perform in opposite ways, opening during inhalation and closing during exhalation. In contrast, mask B has exhaust holes but without exhaust valves, these always being open to the outside. When the subjects exhaled, the exhaled air flowed out through two holes.

Fig. 5 Temporal changes in mean absolute humidity outside (A), inside (B), in the chest wall microclimate (C), and in chest wall skin (D) of the two kinds of masks.

The values are means of each rest and exercise period±SEM (n=10). For definitions of E1, E2, E3 and R1, R2, R3, see Methods.
However, as airflow was in one direction only, some exhaled air remained inside mask B. These differences concerning air exchange between inner and outer mask surface made the microclimate on the inner surface of the mask better (lower temperature and humidity) when wearing mask A. Thus, mask A has better ventilating properties, which contributes to lower microclimate temperature and humidity inside the mask A. The temperature and humidity of the outer surface decrease accordingly. On the other hand, the exhaled air is not dissipated promptly in mask B, which is responsible for higher temperatures and humidities inside the mask microclimate and on the outer surface in mask B as compared to those in mask A.

Nielsen et al. (1987) has shown that whole body thermal sensation was significantly influenced by the mask air temperature. Further, Hayashi and Tokura (2004) found that the rectal and tympanic temperatures increased more slowly wearing the mask with exhaust valves as compared to those without exhaust valves for most subjects. However, none has provided direct scientific evidence to demonstrate that the microclimate temperature and humidity inside the mask significantly influence whole body thermoregulatory responses.

The present results have demonstrated the relationship between the thermal microclimate inside the mask and whole body thermoregulatory responses. Equation 1 has clearly shown that the ear canal temperature was significant augmentation along with increased temperature and humidity inside the mask. The humidity was a more important determinant of the ear canal temperature. This is probably due to the fact that the exhaled air increases heat loss from the body because Burch (1945) reported that in a normal adult in a comfortable ambient environment, the heat loss due to the respiratory tract accounts for approximately 11% of the total heat loss from body, indicating that heat loss from the respiratory tract is of importance for human thermoregulation.

Equation 1 and the above physiological mechanism can account for why the ear canal temperature increases significantly in mask B. As just mentioned, the exhaled air is not dissipated promptly with mask B, which may increase temperature and humidity inside the mask microclimate and decrease heat loss from the respiratory tract, leading to an increased ear canal temperature in mask B. Further, in the present study, the ear canal temperature sensor was placed in
the ear canal near the tympanic membrane, and the canal was heavily insulated by cotton wool to insulate the ear canal from the outside environment. When above precautions were used in the measurement of ear canal temperature, the measured temperatures may reflect tympanic membrane temperature relatively closely (Bhattacharya and McGlothlin, 1996). While Cabanac and Caputa (1979) have shown that tympanic membrane temperature not only reflects brain temperature, but probably reflects it closely. Therefore, a higher brain temperature may have been resulted in the case of mask B. As part of the physiological regulation of body temperature, heat loss from the respiratory tract also affects chest
microclimate temperature. Equations 2 revealed that the chest microclimate temperature showed significant augmentation along with increased temperature inside the mask microclimate. The higher chest microclimate temperature in mask B may have been posed by a higher microclimate temperature inside this mask. The absolute humidity of the chest microclimate and skin were also significantly lower with mask A (Fig. 5), suggesting that local sweating from chest skin might have been smaller with mask A. Sweating is positively linked with core and skin temperatures (Aschoff, 1971) and so the smaller increase of ear canal temperature and chest skin temperature with mask A may be responsible for reducing the amount of sweating. This would result in lower chest microclimate and skin humidities. The maximum heart rate tended to be lower with mask A than that with mask B (Fig. 2). This may be related to the reduced increase of ear canal temperature when wearing mask A, because heart rate is positively linked with tympanic temperature (Cabanac and Caputa, 1979). While ear canal temperature may have reflected membrane temperature relatively in the present study.

The results from the subjective assessment with two kinds of masks are in agreement with results from the studies of Nielsen et al. (1987) and Li (2005), who showed that the thermal sensation of the body is influenced by the thermal microclimate inside the mask and the perception of dampness is positively correlated with humidity in a clothing microclimate. Due to the significantly reduced temperatures and humidities inside the mask and clothing microclimates in mask A, the ratings related to the subjective perceptions feeling humid and hot were significantly better with this mask (Fig. 6). Moreover, as the dampness inside mask A is dissipated promptly, wearing mask A produced significantly less mist over the glasses for the subjects wearing glasses. By means of efficient ventilation, the oxygenous fresh air was inhaled continuously, which might have contributed to less subjective perceptions of feeling unfit, odorous, and fatigued with mask A (Figs. 6 and 7), while that perceived wetness and fatigue significantly influenced perceived overall discomfort when the masks were worn (Equation 3). The subjective perception of feeling humid is the most important factor to overall discomfort (Equation 3), which agrees well with the observations reported by Li (2005).

The previous study has found that the relationship between the mask's filter resistance and the subjective difficult in breathing was linear. Any decrease in the inspiratory resistance of the mask's filter enhanced endurance and performance (Lerman et al., 1983). In the present study, the subjective ratings for breath resistance were significantly lower with mask A (Fig. 6C), suggesting that the inspiratory resistance might have been smaller with mask A. All the above favorable ratings contribute to the subjective preference for mask A (Fig. 8).

In addition, a study on in vivo protective performance of masks A and B was carried out simultaneously. During walking and resting periods, the researcher sprayed a KCl-Fluorescein solution as a surrogate for a viral solution onto the masks twice at a distance of 100 cm every 10 min, as it would be dangerous and unethical to conduct in vivo mask tests by exposing human subjects to live viruses. The simulated viral solution was sprayed on the masks 14 times in total during both walking and resting. Experimental results showed that both masks A and B had near or over 99% protection efficiency for the simulated viral solution, comparing with 97% and 95% filtration efficiencies of N95 and surgical masks. The results suggest the in vivo protective efficiencies of masks A and B are all enhanced as compared to those commercially available masks by simply locating the breathing pathways (exhaust valves and holes) to the back of mask (Li et al., 2006; Guo et al., 2007 unpublished data).

The human brain has evolved to keep the brain temperature constant, which has made mankind prosper. Our results demonstrate convincingly that we should not forget important physiological mechanisms when we design protective masks. The actual use of the mask by a wearer may depend on the availability of better-designed masks, without substantial additional heat stress to the wearer to keep the brain temperature constant. Equation 3 showed that mask A could improve humid and fatigue sensations more efficiently, compared with mask B, suggesting that the usage of mask A could well influence whole bodily perceived sensation. Therefore, we concluded that mask A is better for reducing thermal stress than mask B, by dissipating promptly the exhaled air to increase heat loss from the body.

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References


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