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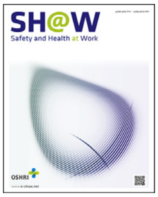

Original article

Water-blocking Asphyxia of N95 Medical Respirator During Hot Environment Work Tasks With Whole-body Enclosed Anti-bioaerosol Suit

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ABSTRACT

Background: During hot environment work tasks with whole-body enclosed anti-bioaerosol suit, the combined effect of heavy sweating and exhaled hot humid air may cause the N95 medical respirator to saturate with water/sweat (i.e., water-blocking).
Methods: 32 young male subjects with different body mass indexes (BMI) in whole-body protection (N95 medical respirator + one-piece protective suit + head covering + protective face screen + gloves + shoe covers) were asked to simulate waste collecting from each isolated room in a seven-story building at 27-28°C, and the weight, inhalation resistance (R_f), and aerosol penetration of the respirator before worn and after water-blocking were analyzed.
Results: All subjects reported water-blocking asphyxia of the N95 respirators within 36-67 min of the task. When water-blocking occurred, the R_f and 10-200 nm total aerosol penetration (P_t) of the respirators reached up to 1270-1810 Pa and 17.3-23.3%, respectively, which were 10 and 8 times of that before wearing. The most penetration particle size of the respirators increased from 49-65 nm before worn to 115-154 nm under water-blocking condition, and the corresponding maximum size-dependent aerosol penetration increased from 2.5-3.5% to 20-27%. With the increase of BMI, the water-blocking occurrence time firstly increased then reduced, while the R_f, P_t, and absorbed water all increased significantly.
Conclusions: This study reveals respirator water-blocking and its serious negative impacts on respiratory protection. When performing moderate-to-high-load tasks with whole-body protection in a hot environment, it is recommended that respirator be replaced with a new one at least every hour to avoid water-blocking asphyxia.

1. Introduction

The global pandemic of respiratory infectious diseases such as severe acute respiratory syndrome, Middle East respiratory syndrome, and novel coronavirus pneumonia (NCP) are mainly transmitted by virus through droplet aerosols respiration and/or contagion, which are characterized by highly infectious, high morbidity, and rapid mutation of virus strains, posing a serious threat to people's life and health [1,2]. During the pandemic outbreak, wearing N95 medical respirator is one of the effective

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ways to prevent viral infection, while healthcare workers (HCWs) working in high-risk environments need whole-body protection (N95 medical respirator + one-piece protective suit + head covering + protective face screen + gloves + shoe covers) [3]. Although whole-body protection provides both respiratory protection and contact prevention, it has the drawbacks of poor air and moisture permeability [4]. Taking the recent outbreak of NCP as an example, during the hot seasons from 2020 to 2022, NCP outbreaks occurred in many group-dormitory buildings in universities, residential buildings, and hotels in China, and to avoid the spread of virus aerosols, the occupants of entire buildings were isolated in their respective rooms. During the isolation period, HCWs in whole-body protection were required to climb each floor of the isolated building to deliver meals and collect waste in front of the door of each isolated room. Existing studies have shown that performing job tasks in whole-body protection could cause negative impacts on the physiology of HCWs [5–8], including increased body temperature and heavy sweating [9,10]. Especially in hot environment, the head and facial skin of HCWs covered by the head covering, respirator, and protective face screen will inevitably sweat a lot. Consequently, the sweat dripping from the scalp and forehead onto the outer surface of the respirator, the sweat generated by the facial skin contacts with the inner surface of the respirator, and the hot humid air exhaled by the HCWs will work together to wet and soak the respirator from both inside and outside [11].It can be predicted that in this scenario, the respirator will absorb a large amount of water/sweat, which will lead to a sharp rise in inhalation resistance [12,13], jointing with the sweat accumulated in the inner cavity of the respirator will worsen HCWs discomfort or even asphyxiation, so that inevitably inducing HCWs to remove their respirators and then to be exposed to viral aerosols in the infectious environment.

Existing studies have already verified that the sweat and exhaled hot humid air can negatively affect the inhalation resistance and filtration efficiency of respirators. Lin et al. reported that when the human face sweats more, the respirator tends to be completely soaked and stick to the wearer's mouth and nose, resulting in the inability to breathe normally [14]. By immersing the N95 respirator into artificial sweat for different time periods, Zhang found that with the prolongation of immersion time, the respirator inhalation resistance increased significantly, while the filtration efficiency decreased significantly, and the tolerance time of the wearer to the respirator with higher inhalation resistance was significantly shortened, indicating that sweat may cause great risk to the comfort and protective performance of the respirator [15]. Li reported that the sweat and oil generated by head and facial skin in contact with the respirator would affect the water barrier performance of the respirator and lead to a reduction in respirator filtration efficiency [16]. Cai et al. confirmed that when wearing a non-valved respirator for a long time, the exhaled hot humid air would condense onto the inner surface of the respirator, leading to a decrease in the filtration efficiency and an increase in the inhalation resistance of the respirator [17]. Hsuan found that when subjects wearing N95 respirators for a long time and accompanied by oral communication, the water vapor and sweat condensation on the respirator would accelerate, resulting in the increase of the inhalation resistance and the wearer physiological load [18]. Roberge et al. [19] evaluated the effect of exhaled moisture on the respiratory resistance of N95 respirators and found that the respirator inhalation resistance increased by 4.21 Pa with 0.26 g absorbed water. Guan et al. evaluated the N95 medical respirators at a simulated human breathing flow (sinusoidal waveform with 2 L/breath, 20 breaths/min, and exhaled water vapor temperature 37°C) in the lab environment (20°C, 65% RH) for over 8 hours, and found that after 8-hour continuously wearing simulation, the moisture permeability of the respirator decreased significantly while the inhalation resistance increased sharply [20].

Literature review showed that most of the existing studies on HCWs wearing respirators or protective clothing against the virus aerosols were conducted at room temperature, and the airborne viruses are generally thought to have difficulty surviving in hot environments. However, the NCP virus, which has been widely spreading in the summer seasons during 2020-2022, has alerted us to the existence of strains that can survive in summer or relatively hot environments [21,22]. In addition, most existing studies examine the negative impact of wearing respirator or whole-body protection on the subjects' physiological parameters and thermal sensation [23,24], and very few studies on the changes in protective performance of the respirator after absorbing water/sweat are limited to simulating the impacts of exhaled hot humid air using breathing simulator. According to the literature review, there is still a lack of research on the water-blocking asphyxia of respirator caused by the combined effect of excessive sweating on the head/face and the exhaled hot humid air when real human subjects in whole-body protection performing tasks in relatively hot environment, as well as the impact of the water-blocking on the inhalation resistance and filtration efficiency of the respirators. In view of this, 32 young male subjects with different heights and weights were recruited to simulate the household waste collection in a seven-story isolated dormitory building at 27-28°C under whole-body protection (N95 medical respirator + one-piece protective suit + head covering + protective face screen + gloves + shoe covers). When the subjects clearly felt water-blocking asphyxia of the respirator, the waste collection activity was terminated and the work time duration was recorded. The weight, inhalation resistance, aerosol penetration, and microstructure of the tested N95 medical respirators worn by each subject were tested before wearing and after water-blocking to quantify the negative effects of water-blocking on the respirator. The research results can serve as reference for respiratory protection of HCWs against viruses transmitted through droplet aerosols.

2. Materials and methods

2.1. Human subjects

32 young male subjects were recruited in this study. The average ± standard deviation of subjects' age, height, weight, and body mass index were 22.5 ± 1.64 years old, 177.8 ± 4.05 cm, 73.3 ± 13.75 kg, and 23.1 ± 3.89 kg/m^2, respectively. All subjects had no history of asthma, cardiovascular disease, or respiratory disease. Considering that BMI is a commonly used international standard for measuring the degree of obesity and health of the human body [25], the BMI span of the 32 subjects is relatively large, ranging from 17.21 to 31.35 kg/m^2. Based on BMI classification, 4 subjects were thin, 16 were normal, 8 were overweight, and 4 were obese. To exclude confounding factors, before the experiment, all subjects were required to shave to have clean faces and wear standardized clothes (including short-sleeved t-shirts, sports pants, short socks, and sports shoes). This study was approved by the medical ethics committee of the First People's Hospital of Xuzhou (approval No. xyy11 [2023] 074), and each subject signed an informed consent form.

2.2. Whole-body protection with N95 medical respirator

The experimental flow chart of this study was presented in Fig. 1. As can be seen, during the experiment, each subject was in a whole-body enclosed anti-bioaerosol suit (i.e., whole-body protection), including disposable N95 medical respirator, disposable one-piece

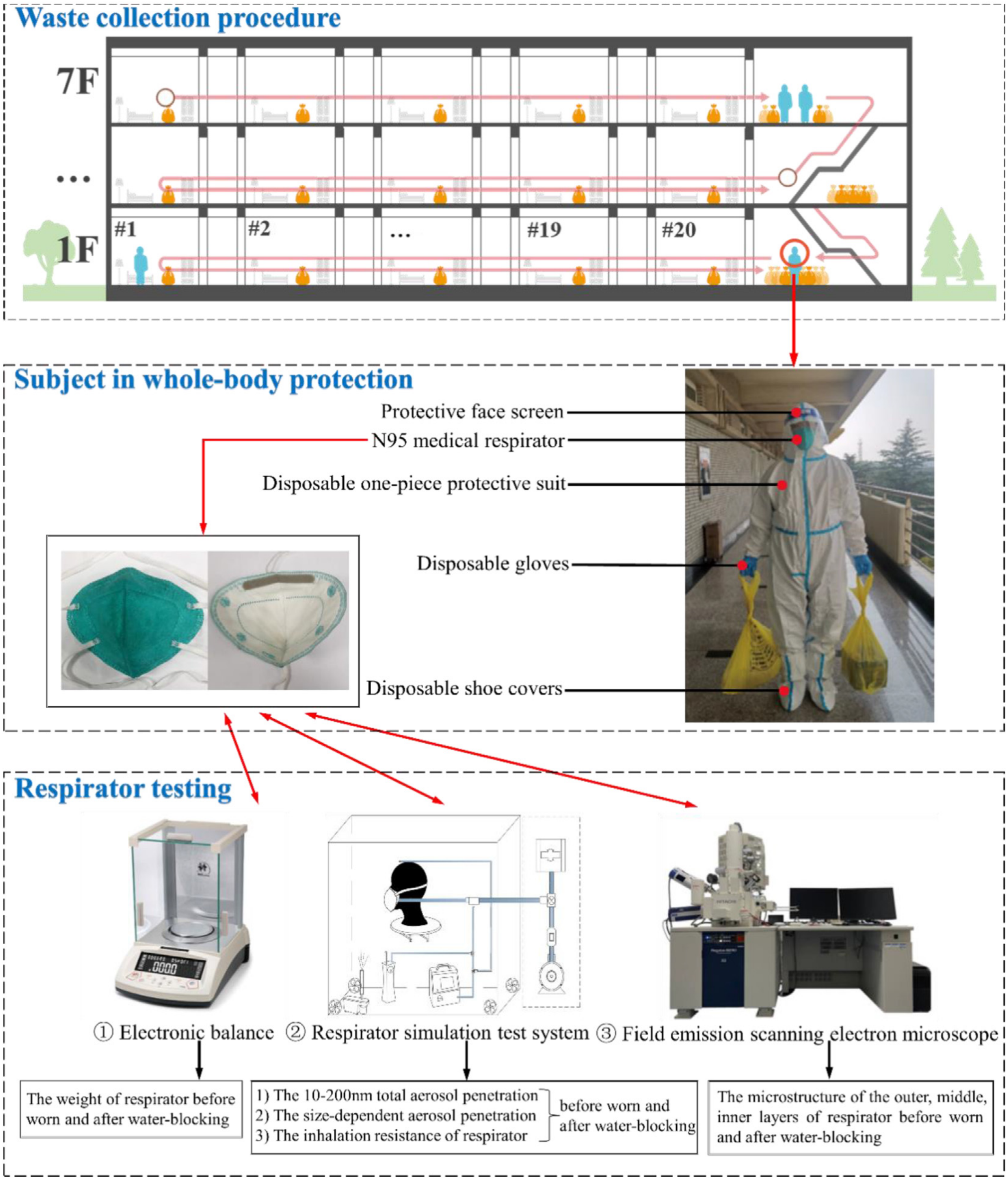

Fig. 1. Experimental flow chart.

protective suit, disposable head covering, protective face screen, disposable gloves, and disposable shoe covers. All above personal protective equipment models selected are commonly used by HCWs during the epidemic.

To be specific, the N95 medical respirator is certified by the China national standard GB19083-2010 [26], which has a three-layer structure, with the outer and inner layers of spunbonded polypropylene and the middle layer of melt-blown polypropylene. The disposable one-piece protective suit is made of polypropylene non-woven fabric, one-piece structure, consisting of a hooded top and pants, with elastic closure at the cuffs, ankle opening, hat face, waist, and heat-sealing of the joints with pressure strips. The disposable one-piece protective suit, disposable head covering, protective face screen, disposable gloves, and disposable shoe covers all comply with the China national standard GB19082-2009 [27].

2.3. *Experimental scheme*

As shown in Fig. 1, the experiment was conducted in a group dormitory building with seven floors and 20 rooms on each floor. There is a 5 m interval between the doors of two adjacent rooms, and one bag of simulated household waste weighing 2 kg was placed in front of each room door. The air temperature and relative humidity during the experimental process were 27-28°C and 50-60%, respectively. Before each experiment, the weight, inhalation resistance, aerosol penetration, and microstructure of the respirator to be worn by each subject were tested. During the experiment, the subjects in whole-body protection performed waste collection layer by layer from the 7th floor, and it was required for all waste on each floor to be firstly collected at the stairway and then moved down to the lower floor. The experiment was terminated when the water-blocking of the

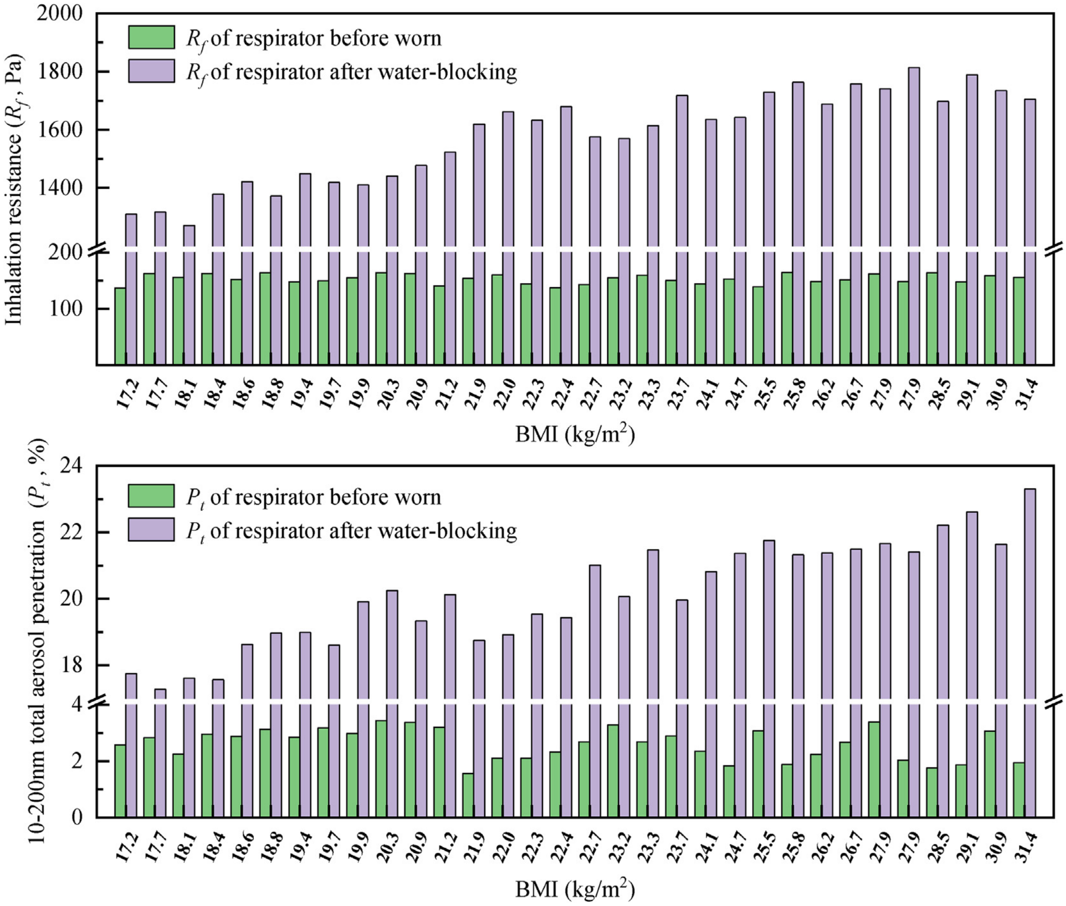

Fig. 2. Inhalation resistance (R_f) and 10-200 nm total aerosol penetration (P_t) before the respirator was worn and after water-blocking occurred.

respirators made the subjects feel suffocated, and the work time duration (T) was recorded. Throughout the experimental process, subjects performed three specified exercises corresponding to specific levels of metabolic exertion, including collecting waste on each floor, carrying waste down one floor, and climbing up one floor with empty hands. According to the relevant actions classified in ISO 8996-2021 [28], the metabolic rates of collecting waste on each floor and carrying waste down one floor are about 235-360 W, which are moderate workloads, while the metabolic rate of climbing up the stairs should be greater than 465 W, belonging to high workload. After the experiment, the respirator was carefully taken off and immediately sent to the lab for weight, inhalation resistance, aerosol penetration, and microstructure testing again, and the results were compared with those before the experiment.

2.4. Respirator weight, inhalation resistance, aerosol penetration, and microstructure testing

As presented in Fig. 1, the tested respirator was weighed before and after the experiment with an electronic balance (ME204, Mettler Toledo, Switzerland), thus the weight of the respirator absorbed water (ΔW) when water-blocking occurred was obtained. The inhalation resistance and aerosol penetration of the respirator before and after the experiment were tested using a self-developed respirator simulation test system (refer to Zhu et al., 2022 [29] for more details on this test system), the main body of which was a 2.2 m × 2.2 m × 2.2 m test chamber in which the aerosol generator continuously released 10-200 nm NaCl aerosols at a steady flow rate. The respirator placed in the center of the test chamber was fully sealed on the manikin head form with silicone adhesive. For the inhalation resistance test, a constant flow of 85 L/min was generated by a vacuum pump (Model VP 2200, HFS, Covina, CA, USA) as the testing flow, and the difference in air pressure between the inside and outside of the respirator was measured using a manometer (AirflowTM PVM100, TSI Inc., USA) to obtain the respirator inhalation resistance (R_f). During the aerosol penetration test, a simulated human breathing flow of 85 L/min was generated by a self-developed breathing simulator (for more details on the breathing flow simulation, please see Zhu et al., 2022 [30]) as the testing flow, and the total (10-200 nm) and size-dependent (centered at 15.4, 20.5, 27.4, 36.5, 48.7, 64.9, 86.6, 115.5, and 154 nm) number concentrations of NaCl aerosols inside and outside the respirator were measured using a NanoScan SMPS Nanoparticle Sizer (Model 3910, TSI Inc., USA) to respectively obtain the total (P_t) and size-dependent aerosol penetration (P_{dp}) of the respirator. The microstructure of the three layers of the respirator before and after the experiment was analyzed by a field emission scanning electron microscope (SU8200, Hitachi, Japan).

2.5. Data analysis

For each subject, the R_f, P_t, P_{dp}, most penetration particle size (MPPS), and maximum size-dependent aerosol penetration ($P_{dp\text{-}max}$) before the respirator was worn and after water-blocking occurred were quantitatively compared. The relationship functions of R_f versus ΔW, P_t versus ΔW, T versus BMI, ΔW versus BMI, R_f versus BMI, and P_t versus BMI were plotted and tested for linear correlation using Pearson's correlation coefficient. Linear regression was preferred when it was significant, because linear fitting was more intuitive and its slope conveys the key message of "how the dependent variable (DV) changes along with per unit change in the independent variable (IV)". It was found that linear regressions could well fit the relationships of R_f (DV) versus ΔW (IV), P_t (DV) versus ΔW (IV), ΔW (DV) versus BMI (IV), R_f (DV)versus BMI (IV), and P_t (DV) versus BMI (IV). Meantime, polynomial regression was performed for BMI (DV) versus T (IV) since linear regression was not significant ($p > 0.05$).

3. Results

3.1. Comparison of inhalation resistance (R_f) and 10-200 nm total aerosol penetration (P_t) before the respirator was worn and after water-blocking occurred

Fig. 2 presents the R_f and P_t of each subject's N95 medical respirator before wearing and after water-blocking. As can be seen, the R_f and P_t of these 32 respirators before they were worn were 137-164 Pa and 1.56-3.44%, respectively, all in accordance with the China national standard GB19083-2010, in which the R_f and P_t should be less than 343 Pa and 5%, respectively [26]. When water-blocking occurred, the respirator R_f and P_t abruptly increased up to 1271-1814 Pa and 17.28-23.30%, respectively, approximately 10 and 8 times increase from the baseline values, far exceeding the corresponding limit values specified in GB19083-2010 [26].

Fig. 3 shows the scanning electron microscope images of the outer, middle, and inner layers of the respirator before it was worn and after water-blocking. As presented in Fig. 3, the outer and inner layers consisting of spunbonded polypropylene both showed relatively uniform fibers of about 20 μm in diameter, forming a random fiber network. The melt-blown polypropylene in the middle layer consists of two types of fibers of about 8 μm and 2 μm in diameter, constituting a three-dimensional disordered spatial network [31,32]. When water-blocking occurred, only a small amount of aerosol residue was found to deposit on the middle and inner layers of the respirator (see Fig. 3), which should not be the main reason for the abrupt increase in the R_f. The middle layer of melt-blown polypropylene was waterproof with a lower water vapor transmission rate [33], resulting in higher contact angle when water/sweat droplets with higher surface energy contact with the waterproof polypropylene surface with low surface energy [19,34]. Moreover, due to the high temperature and water vapor content of the internal microenvironment of the respirator, the temperature difference between the respirator and the external environment will lead to condensation of water vapor inside the microenvironment and onto the fibers of the respirator, blocking the pores between the filter fibers [35,36], and thus increasing the airflow resistance. When HCWs perform moderate to high job tasks, the required inspiratory flow, breathing frequency and relative humidity of exhaled air all increased [37,38], and when the inhalation

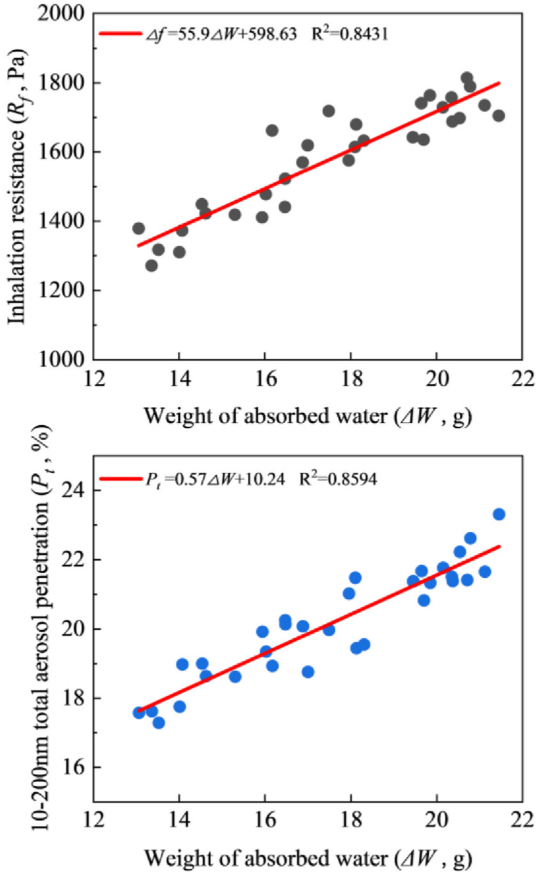

Fig. 4. Relationship between inhalation resistance (R_f), 10-200 nm total aerosol penetration (P_t), and weight of absorbed water (ΔW) when respirator water-blocking occurred.

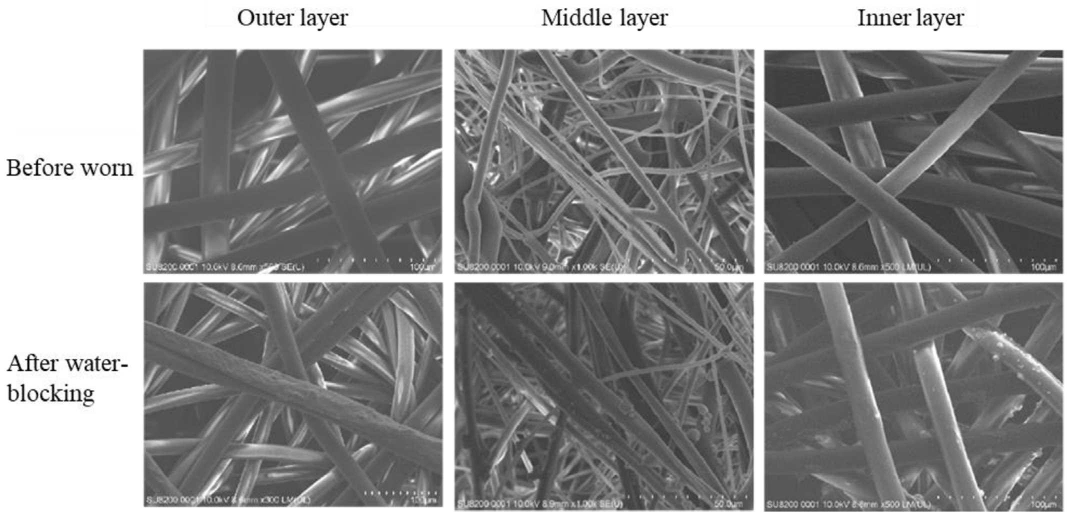

Fig. 3. Scanning electron microscope images of the outer, middle, and inner layers of the respirator before worn and after water-blocking.

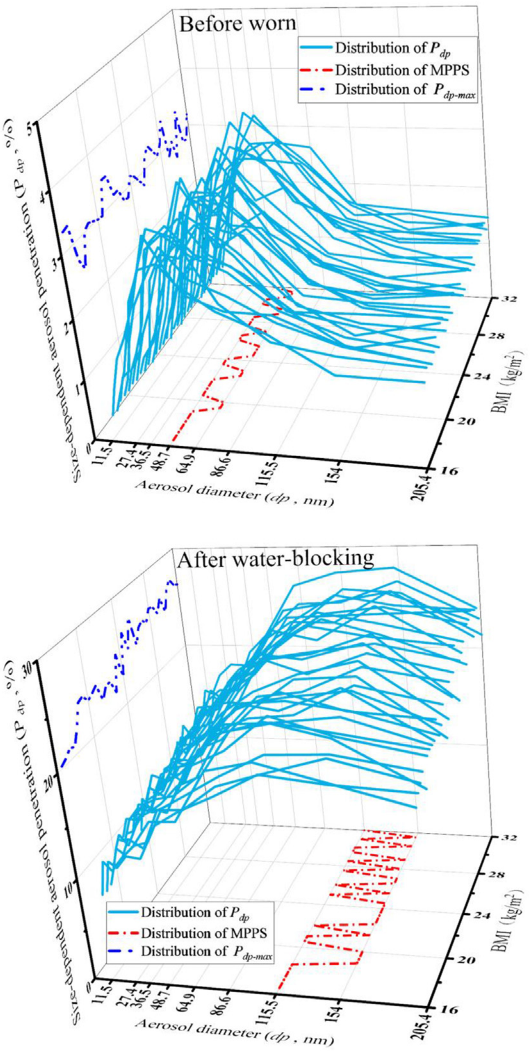

Fig. 5. The size-dependent aerosol penetration (P_{dp}), most penetration particle size (MPPS), and maximum size-dependent aerosol penetration ($P_{dp\text{-}max}$) of 32 respirators before worn and after water-blocking.

resistance was too high, continuously wearing the respirator was likely to cause an increase in carbon dioxide content and a decrease in oxygen content in the respirator cavity [39,40], making it hard for the HCWs in hot environment to breathe normally.

As the core fiber layer for aerosol filtration, the melt-blown polypropylene has five filtration mechanisms including gravitational settlement, inertial collision, interception, Brownian diffusion, and electrostatic attraction [41]. Among which, the electrostatic attraction plays a crucial role in filtering nanoscale and submicron aerosols [42]. The sweat dripping from the scalp and forehead onto the outer layer of the respirator, the sweat generated from the facial skin contacts with the inner layer of the respirator, and the exhaled hot humid air will work together to wet and soak the respirator from both inside and outside, which will neutralize the electrostatic charge on the electret fibers [43,44], significantly reducing their ability to catch 10-200 nm aerosols, and correspondingly leading to a significant increase in the aerosol penetration.

Fig. 4 shows the regression of the R_f and the P_t on ΔW when water-blocking occurred, and it was found that with the increase of the ΔW, both R_f and P_t increased significantly, which is consistent with the above analysis on the middle layer of the respirator. To be specific, with the increase of the ΔW, the R_f increased linearly with the slope of 56 Pa/g, indicating that when water-blocking occurred, each additional gram of water/sweat absorbed by the respirator would result in a 56 Pa rise in the respirator inhalation resistance. Similarly, it can be seen that with the increase of the ΔW, the P_t increased uniformly as a linear function with the slope of 0.57%/g, indicating that when water-blocking occurred, each additional gram of water/sweat absorbed by the respirator would result in a loss of 0.57% in the respirator filtration efficiency. Analysis of the reason is that as the amount of absorbed water increased, the fiber pores were continuously blocked, thus the respirator inhalation resistance kept increasing. Meanwhile, the fibers' ability to capture aerosols by electrostatic adsorption was continuously weakened, leading to the decay of the respirator filtration efficiency with increasing ΔW.

3.2. Comparison of size-dependent aerosol penetration (P_{dp}), most penetration particle size (MPPS), maximum size-dependent aerosol penetration ($P_{dp\text{-}max}$) before the respirator was worn and after water-blocking occurred

Fig. 5 presents the comparison of the P_{dp}, MPPS, and $P_{dp\text{-}max}$ of 32 respirators before they were worn and after water-blocking. As can be seen, the P_{dp}, MPPS, and $P_{dp\text{-}max}$ of respirators before they were worn, respectively, ranged from 0.35 to 3.30%, 48.7 to 64.9 nm, and 2.49 to 3.49%, which were all in accordance with GB19083-2010. When water-blocking occurred, the P_{dp}, MPPS, and $P_{dp\text{-}max}$ respectively raised from 8.08 to 21.23%, 115.5 to154.0 nm, and 20.22 to 27.45%, leading to none of the 32 respirators in accordance with GB19083-2010.

The reasons for the above changes were analyzed as follows: the melt-blown polypropylene, as the core filtration layer of the respirator, mainly relies on electrostatic attraction to capture nano- to submicron-sized aerosols, especially submicron aerosols [45,46]. Before the respirator was worn, the electrostatic attraction could effectively work, thus the overall P_{dp} of the respirator in the aerosol size range of 10-200 nm was low, and in comparison, the P_{dp} in the nanometer size range of 10-100 nm was relatively higher than that of submicron size range of 100-200 nm, thus the MPPS and the corresponding $P_{dp\text{-}max}$ occurred in the nanoscale size range (48.7-64.9 nm). However, when water-blocking occurred, a large amount of water vapor and sweat condensed on the electret fibers, which greatly weakened the electrostatic attraction of the respirator, resulting in a significant increase in the overall P_{dp} within the 10-200 nm aerosol size range. However, given that electrostatic attraction has a stronger ability to capture submicron aerosols within the 100-200 nm size range [47,48], when the electrostatic attraction was weakened, the increase in P_{dp} within 100-200 nm was more significant compared to the nanoscale size range of 10-100 nm, resulting in the MPPS of the respirator shifted from the nanoscale of 48.7-64.9 nm to the submicron of 115.5-154.0 nm, and the corresponding $P_{dp\text{-}max}$ soared from 2.49-3.49% to 20.22-27.45%.

3.3. Relationship between work time duration (T), weight of absorbed water (ΔW), inhalation resistance (R_f), 10-200 nm total aerosol penetration (P_t), and subjects' BMI when respirator water-blocking occurred

Fig. 6 presents the relationship between T, ΔW, R_f, P_t, and subjects' BMI when respirator water-blocking occurred. It can be clearly seen from Fig. 6 (a) that all 32 young male subjects in whole-body protection reported respirator water-blocking asphyxiation within 36-67 min of moderate to high workload tasks in 27-28°C hot environment. Moreover, as the subjects' BMI increased, the T first increased and then decreased, presenting a single peak distribution. To be specific, when the BMI was <18 kg/

m^2, the T was <47 min, and when the BMI was 22 kg/m^2, the T peaked at 67 min, while when the BMI was >28 kg/m^2, the T dropped below 40 min. Fig. 6 (b) shows that the ΔW was positively and linearly correlated with the BMI, and with the BMI increase from 17 to 32 kg/m^2, the ΔW increased from the minimum 13 g to the maximum value of 22 g. From Fig. 6 (c), it is found that with the BMI increased from 17 to 32 kg/m^2, the R_f of respirator under water-blocking condition rose linearly from 1300 Pa to 1800 Pa. Fig. 6 (d) shows that as the subjects' BMI increased, the P_t of respirator under water-blocking condition linearly increased from 17.28% to 23.30%. Furthermore, the slopes of the linear functions listed in Fig. 6 (b), (c), and (d) indicate that when respirator water-blocking occurred, per unit (i.e., 1 kg/m^2) increase of subjects' BMI would result in a 0.63 g increment in the absorbed water by the respirator, a 36 Pa rise in respirator inhalation resistance, and a 0.37% loss in respirator filtration efficiency, respectively.

The reason for the above changes is that as the BMI increases, the subjects' body shape gradually changes from thin to normal to fat, and their physical fitness also tends to first rise then fall. For subjects with lower BMI and thin body shape, although their ΔW and respiratory flow were relatively lower (see Fig. 6 (b)), those subjects also have relatively lower respiratory muscle tolerance [49], and compared with those with normal BMI, they reported water-blocking asphyxia of respirator earlier (see Fig. 6 (a)). Subjects with higher BMI and fatter body are more likely to sweat [50,51] and have higher respiratory flow, resulting in a higher ΔW (see Fig. 6 (c)) and R_f (see Fig. 6 (c)), leading to both earlier reports of respirator water-blocking (see T in Fig. 6 (a)) and higher P_t (see Fig. 6 (d)) than those with lower BMI and thin body shape [52].

4. Limitations

4.1. Only one respirator model—the "N95 medical respirator" was tested in this study

"N95 medical respirator" is an official terminology certified by the China national standard GB 19083-2010 [26], which has protective properties comparable to those of the surgical N95 respirator regulated by the U.S. Food and Drug Administration Code of Federal Regulations (CFR) Title 21 CFR 878.4040 [53] and the U.S. Centers for Disease Control and Prevention National Institute for Occupational Safety and Health 42 CFR Part 84 [54]. It should be noted that China's KN95 respirator certification standard GB 2626-2019 [55] is almost the same as the U.S. N95 respirator certification standard 42 CFR Part 84 [54]. To be specific, the KN95 respirator testing conditions (challenge medium: NaCl aerosols with count

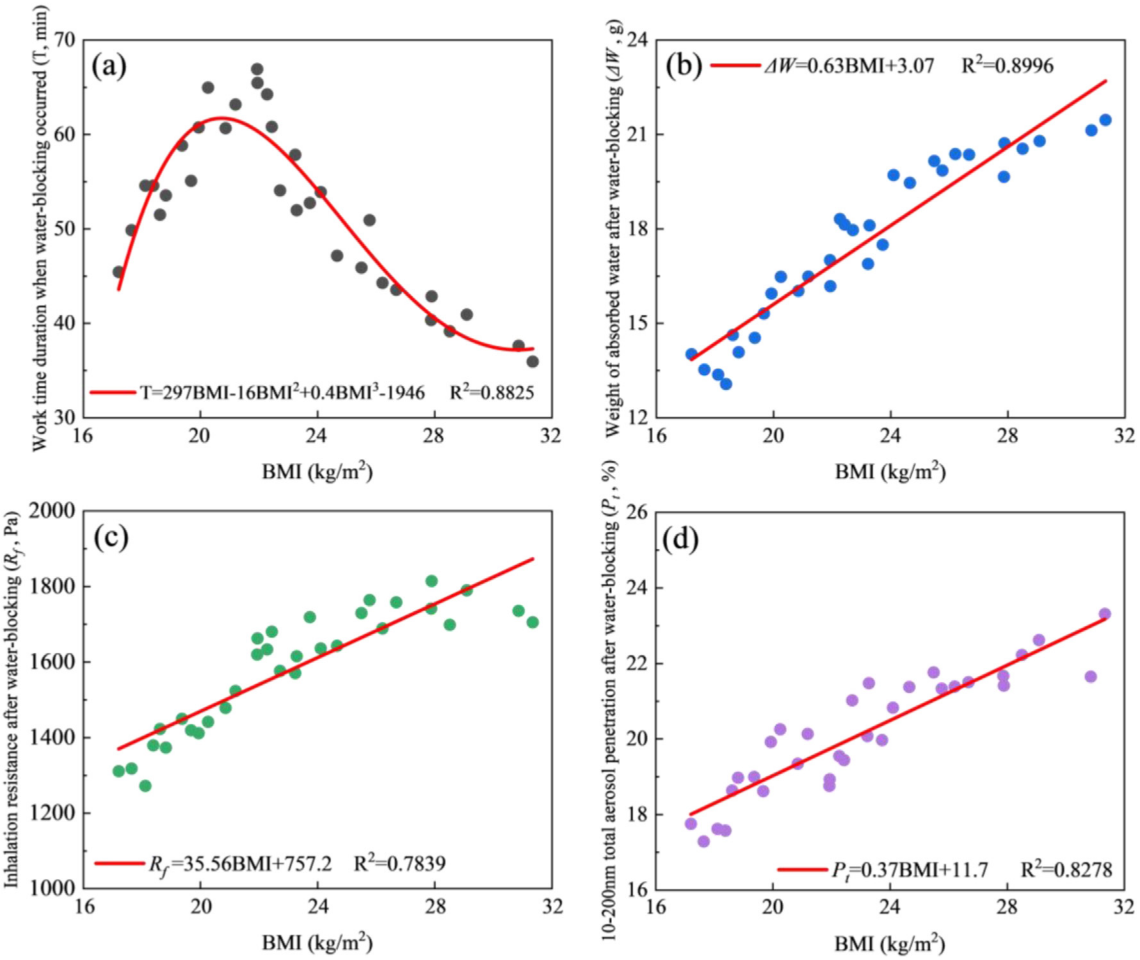

Fig. 6. Relationship between work time duration (T), weight of absorbed water (ΔW), inhalation resistance (R_f), 10-200 nm total aerosol penetration (P_t) and subjects' BMI when respirator water-blocking occurred.

median diameter 0.075 ± 0.020 μm; testing flow: 85 L/min), filtration efficiency (≥95%), and inhalation resistance (≤343 Pa) are identical to the N95 respirator [54,55]. According to China national standard GB 19083-2010 [26], the “N95 medical respirator” not only complies with the filtration efficiency ≥95% for NaCl aerosols with count median diameter 0.075 ± 0.020 μm and inhalation resistance ≤343 Pa under the test flow of 85 L/min (i.e., the “N95 medical respirator” has the same defensive capacity as the N95 and KN95 respirators against aerosols), but also has the function of resisting the permeation of body fluids/blood. The KF94 respirators are certified by the Korean Ministry of Food and Drug Safety under Notice No. 2015-69 with filtration efficiency ≥94% for NaCl aerosols (mass median aerodynamic diameter 0.4 μm) or paraffin oil mist under testing flow of 95 L/min and inhalation resistance ≤7.2 mm H_2O at testing flow of 30 L/min, which also does not have the function of resisting the permeation of body fluids/blood as N95 and KN95 respirators [56].

In summary, the N95, KN95, and KF94 respirators do not have the function of resisting the permeation of body fluids/blood. Thus, they are mainly used to protect against dust particles/aerosols in industrial settings. The “N95 medical respirator” selected in this study is a typical surgical N95 respirator used in hospital environments in China, and its filtration efficiency and inhalation resistance test results before worn meet the protection requirements of N95 and KN95 respirators. Therefore, only this “N95 medical respirator”, which has both high filtration efficiency for aerosols and the function of resisting the permeation of body fluids/blood, was tested.

4.2. *No female was included in the study*

All 32 young male subjects were openly recruited healthy graduate students, which was a convenience sample. Although recruitment of female volunteers was considered in the original experimental design, few female volunteers were willing to join the “simulated waste collection in whole-body protection”, which may be due to concerns about the impact of heavy sweating on a personal image, the worry about exhausting task, the hate of the heavy sweating feeling, and/or the fear of suffocation feeling when respirator water-blocking occurred. Literature review shows that many studies are focusing on the effect of gender differences on facial dimensions, thus influencing the face seal leakage or face fit of the respirators [57–60], and some studies have investigated the gender difference in the sweat response during different types of exercises [61,62]. However, there is still a research gap on the effect of sweating on the protective performance of respirators under gender differences, which needs to be further investigated.

4.3. *Water may be evaporated or lost during transportation from the group dormitory building to the lab*

After the experiment, the respirator was carefully taken off and fully sealed into a previously weighed inflated plastic bag, with the ear straps clapping in the opening of the plastic bag for handholding, thus avoiding the respirator touching too much with the inner side of the inflated plastic bag. The respirator, together with the plastic bag, was immediately carried to the lab for weight testing (the lab was very close to the group dormitory building chosen to carry out the experiment and could be reached within 3-5min). That is, the weight of the respirator that absorbed water was tested first. Following that, the respirator was carefully removed from the inflated plastic bag and fully sealed onto a manikin head form for inhalation resistance and filtration efficiency testing, successively (please see reference [29] for more details), which could be finished within 5 minutes. Finally, the respirator was sent for microstructure testing. Based on the above descriptions, although we tried our best to preserve the exact condition of the respirator immediately after the experiment and to avoid water evaporation or loss during transportation, the status of the delivered respirators may still be different from the initial one immediately after the investigation.

5. Conclusion

This study revealed water-blocking asphyxia of N95 medical respirator during moderate to high workload tasks with whole-body protection in hot environment, and compared the inhalation resistance and aerosol penetration of the respirator before it was worn and after water-blocking. The main conclusions were summarized as follows:

1) During simulated waste collecting process in 27-28°C hot environment, all 32 young male subjects in whole-body protection reported water-blocking asphyxia of N95 medical respirator within 36-67 min, and with the increase of the subjects’ BMI, the water-blocking occurrence time firstly increased then decreased.
2) When water-blocking occurred, the inhalation resistance and 10-200 nm total aerosol penetration of the N95 medical respirators were 1270-1810 Pa and 17.3-23.3%, respectively, which were about 10 and 8 times that of the corresponding values of the respirators before they were worn.
3) Under the water-blocking effect, the size-dependent aerosol penetration, most penetration particle size and maximum size-dependent aerosol penetration of the N95 medical respirators, respectively, increased from 0.3-3%, 49-65 nm, 2.5-3.5% before they were worn to 8-21%, 115-154 nm, and 20-27% under water-blocking condition.
4) With the increase of the subjects’ BMI, the respirator absorbed water increasing linearly from 13 g to 22 g, the inhalation resistance increased from 1300 Pa to 1800 Pa in negative quadratic form, and the 10-200 nm total aerosol penetration increased linearly from 17.5% to 23%.
5) When performing moderate to high workload tasks with a whole-body enclosed anti-bioaerosol suit in the hot environment, it is recommended that the respirator be replaced with a new one at least every hour to avoid the occurrence of respirator water-blocking asphyxiation.

Author contributions

Jintuo Zhu and Xinjian He contributed to the conception or design of the work. Jintuo Zhu, Qijun Jiang and Yuxuan Ye contributed to the acquisition, analysis, or interpretation of data for the work. All authors contributed to drafting the work or revising it critically for important intellectual content; provided final approval of the version to be published; and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Institution and ethics approval and informed consent

This study was approved by the medical ethics committee of the First People's Hospital of Xuzhou (approval No. xyy11 [2023] 074) and each subject signed an informed consent form.

Conflicts of interest

The authors declare no conflicts of interest.

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