Industrial Health 2023, **61**, 275–282

Case Report

Comparison of respiratory protection during exercise tasks between different methods of wearing replaceable particulate respirators and powered air-purifying respirators

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Received November 10, 2021 and accepted April 25, 2022
Published online in J-STAGE May 13, 2022
DOI https://doi.org/10.2486/indhealth.2021-0268

Abstract: This study evaluated the differences in respiratory protection between replaceable particulate respirators (RPRs) and powered air-purifying respirators (PAPRs) based on different wearing methods during exercise tasks. Ten participants wore RPRs and PAPRs alternately in ways comparable to those adopted by workers in actual workplaces. We measured the fit factor of the respiratory protective equipment (RPE) during exercise tasks for each wearing variation. The exercise load was set to 80W using an ergometer. The exercise tasks comprised five actions described in the Japan Industrial Standard T8150 in 2018. We compared the results with experimental data obtained at rest in our previous studies. The fit factor of RPRs during exercise was significantly lower than (p<0.001) and about half that measured at rest, indicating inadequate respiratory protection. On the other hand, the fit factor of PAPRs during exercise tasks was also significantly lower than (p<0.001) and about half that at rest, but respiratory protection was maintained. This suggests that the protection provided by PAPRs is independent of wearing method during exercise. PAPRs may thus be better than RPRs for workers who have to wear RPE inappropriately due to health problems.

Key words: Particulate respirator, Powered air-purifying respirator, Fit factor, Respiratory disease, Occupational hygiene

Introduction

Although the number of cases of pneumoconiosis and occupational diseases due to complications of pneumoconiosis in Japan decreased to 127 in 2020, new cases are still occurring[1)]. The risk of pneumoconiosis and its complications can be reduced by implementing technical and work control measures. In the case that such measures are insufficient, wearing respiratory protective equipment (RPE) can help reduce workers' inhalation exposure to dust and toxic chemicals and prevent these and other occupational diseases. However, previous studies have shown that RPE that lack sufficient adhesion to the face provide inadequate respiratory protection[2, 3)]. For this reason, the

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Ministry of Health, Labour and Welfare in Japan has issued guidelines on matters to consider when selecting and using RPE[4]. Previous studies have shown that there are various ways to wear RPE in Japanese dusty workplaces. We previously reported several inappropriate methods of wearing RPE, including placing the tightening strap over a helmet or a knit cover between the RPE and face[5]. When the performance of RPEs is degraded, it increases the wearer's risk of respiratory diseases such as pneumoconiosis and lung cancer, which can result from inhaling dust and toxic chemicals.

In our previous study, we evaluated the difference in protective performance between replaceable particulate respirators (RPRs) and powered air-purifying respirators (PAPRs) by having participants wear them at rest in various ways in a laboratory[6]. We found that the average leakage rate at rest ranged from 1.82% to 10.92% for RPRs and 0.18% to 0.42% for PAPRs. At rest, while different wearing methods caused a decrease in respiratory protection with RPR, no significant effect was observed with PAPR. This indicates that PAPRs can provide sufficient protection for workers who are unable to wear RPRs properly due to health problems[6]. Because our study on the effect of wearing method on respiratory protection at rest found that PAPRs maintained high respiratory protection regardless of the wearing method, we hypothesized that PAPRs may maintain high respiratory protection regardless of workload. However, we were unable to verify the effect of workload on respiratory protection in our previous study.

Here, we verified the effect of workload on RPE respiratory protection during exercise under different RPE wearing methods. The purpose of this study was to measure the fit factor of RPEs in a laboratory when worn using various methods to determine the effect of wearing method on protection and to contribute to ensuring sufficient respiratory protection by RPEs.

Subjects and Methods

Study design and setting

We conducted a crossover comparison study of 10 participants who agreed to participate in the experiment. The fit factor of each combination of factors (RPE type and wearing method; hereafter referred to as "wearing variation") was measured in two physical states (resting and exercise state). Fit factor (details to follow) is the numerical result of a quantitative fit test performed on an RPE face piece that indicates the effectiveness of the seal against the face. The experiment was conducted from August to September 2018 in an artificial climate chamber at the University of Occupational and Environmental Health, Japan, to eliminate the effect of environmental factors. The temperature and relative humidity in the artificial climate chamber were set to 20°C and 50%, respectively.

Participants

We recruited participants from the University of Occupational and Environmental Health, Japan. All participants were healthy adults over 20 yr old and non-smokers, to prevent tobacco dust from affecting the leakage rate measurement. Ten participants, eight males (mean age [standard deviation (SD)]: 32.1 [3.98] yr) and two females (mean age [SD]: 34.0 [5.0] yr), were eligible for this study.

Particulate respirator

The RPR model selected for the test was 1180–05 (Koken Ltd., Chiyoda, Tokyo, Japan) and the PAPR model was BL–321S (Koken Ltd., Chiyoda, Tokyo, Japan). The RPR consisted of a half facepiece and a single filter with a shape similar to that of the BL–321S. The RPR model complied with RL2 and had a particulate filtering efficiency according to the Japanese standard for dust masks of 95%[7]. The PAPR model complied with PL1 and had a particulate filtering efficiency according to the Japanese standard for PAPRs of 95%[8]. The specifications of the PAPR are as follows: motor blower capacity, large airflow volume type leakage rate, B (less than 5.0%); filtering efficiency, PL1 (over 95.0%). The leakage rate was determined using the following equation:

(Concentration of sodium chloride particles inside PAPR) / (Concentration of sodium chloride particles outside PAPR) × 100

Filter efficiencies of both masks were tested using dioctyl phthalate (DOP) particles, which are essential for assessing protection against liquid particles. While the Japanese certification system contains a standard for solid particles tested using sodium chloride, no half facepiece PAPRs commercially available in Japan have been tested with sodium chloride. For this reason, both masks in this study were tested for liquid particles.

To minimize the influence of each individual's ability to accurately fit the RPE, the participants put on their RPE while looking in a mirror. The tightness of the tightening straps was measured using a force gauge (Sensor Interchangeable Amplifier, eZT, IMADA Co., Ltd, Toyohashi, Aichi, Japan), and was adjusted so that the RPE adhered to the participant's face with even pressure.

Wearing variations

The methods by which participants wore the RPEs were based on the commonly observed methods used the workplace[5] revealed in our previous study. They were as follows:

Method R (the recommended method): The headband was strapped from the parietal region to the occipital region with nothing between the facepiece cushion and the face.

Method K: A knit cover was placed between the facepiece cushion and the face.

Method H: The headband was placed over a helmet.

Figure 1 shows images of the different wearing methods. We represented each wearing variation by combining either "RPR" or "PAPR" with "wearing method." For example, a PAPR worn according to the recommended method (R) was referred to as PAPR_R. Our experiment examined six wearing variations: RPR_R, RPR_K, RPR_H, PAPR_R, PAPR_K, and PAPR_H.

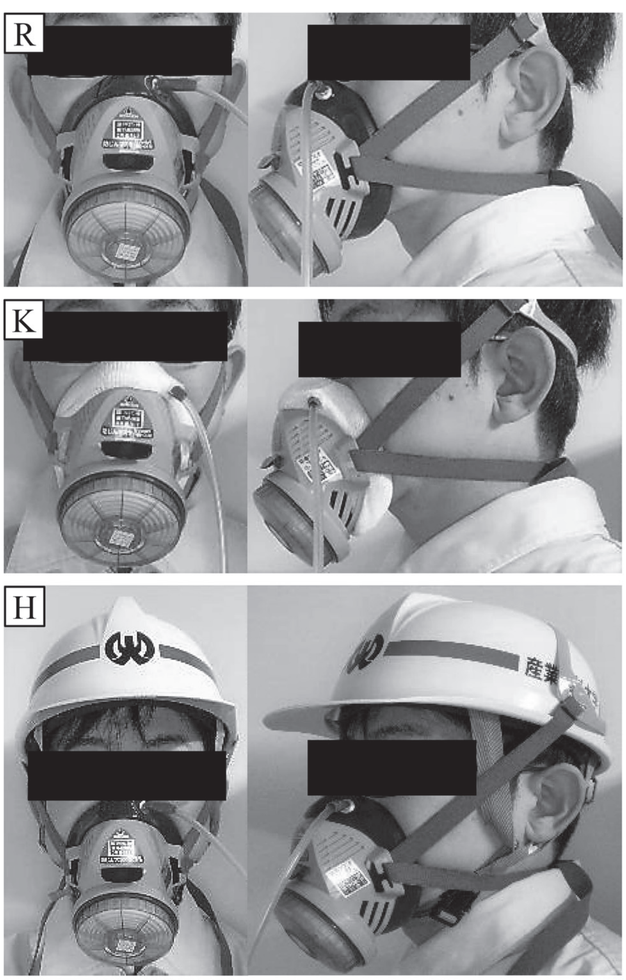

Fig. 1. Photographs depicting different wearing methods, using a replaceable particulate respirator as an example. We adapted these photos from the study by Sekoguchi *et al*[6].

Measurement procedure

We measured the fit factor of each RPE at two physical states, at rest and during exercise, for the six different wearing variations. We reported the experimental data from the resting state in a previous study[6]. For the exercise state, a load of 80 W was set using an ergometer. The order in which the wearing variations were measured for fit factor was assigned randomly. Figure 2 illustrates the measurement procedure.

Measurement of fit factor

To measure fit factor, participants wearing the particulate respirators were asked to perform five actions: 1. Normal breathing, 2. Deep breathing, 3. Turning the head side-to-side, 4. Moving the head up and down, and 5. Talking. During the talking action, the participants repeatedly vocalized "A, I, U, E, O." Each action was performed for 1 min. Prior to starting the measurement in the exercise state, participants performed the exercise for 10 min; the measurement was then performed with exercise. A mask-fit tester (see below) measured the concentration of airborne particles inside and outside the RPE.

The fit testing procedure according to the Occupational Safety and Health Administration (OSHA) specifies that seven motions should be performed to measure the fit factor[9]. However, because the measurement was to be performed during exercise tasks, the five motions described in the Japan Industrial Standard (JIS) T8150 in 2018 were adopted for safety reasons[10]. To eliminate the effect of participant's fatigue on the measurements, fit factor measurements during exercise tasks were limited to two times per day, with an interval of at least one hour.

Apparatus used to measure fit factor

The leakage rate was measured using an MT–03 mask-fit tester (Sibata Scientific Technology Ltd, Soka, Saitama, Japan), which uses a light scattering system to measure the concentration of particles in the air sampled from inside and outside the RPE at 1 l/min. An overview of the measurement procedure is shown in Fig. 3. After measuring the concentration outside the RPE for 17 s, the instrument measured the concentration inside the RPE for 17 s. There was a 10-s interval between samplings from inside and outside the RPE to purge residual particles from the

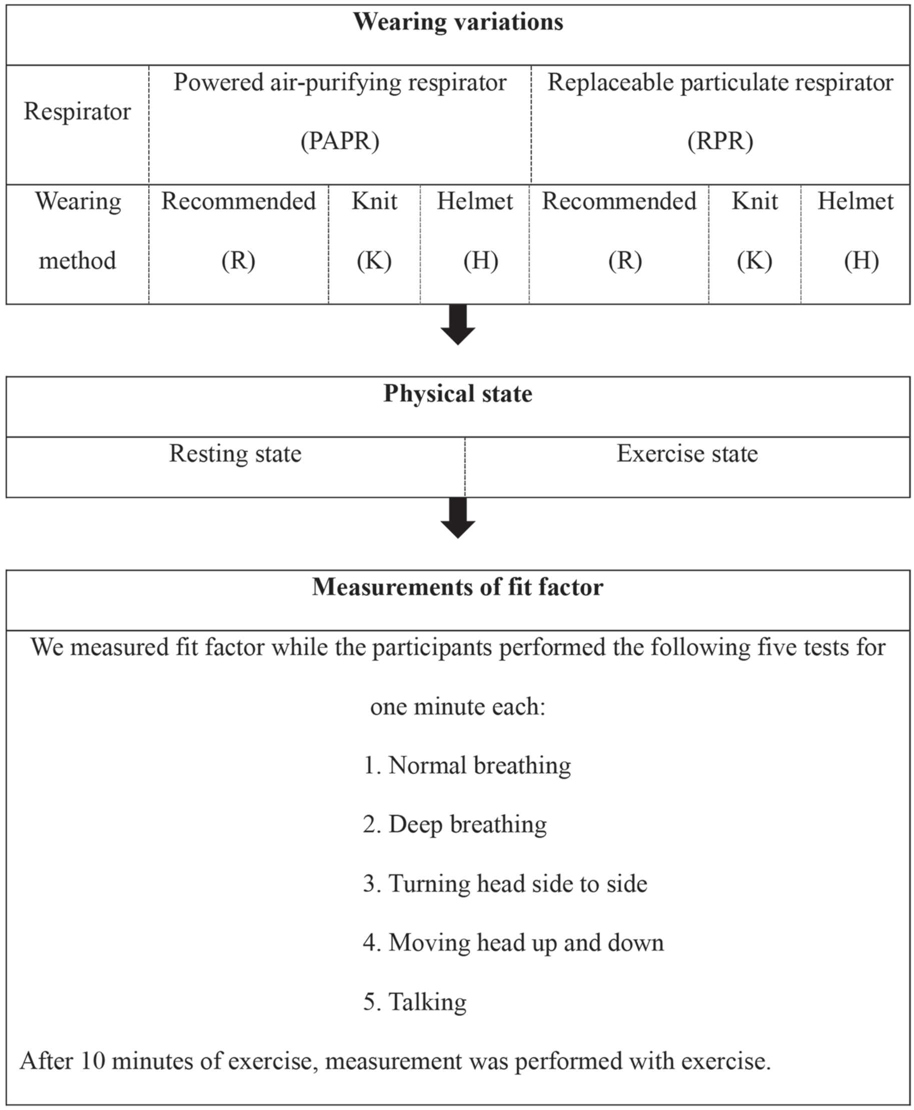

Fig. 2. Outline of the study.

sampling tubes and tester. The total time required for each leakage rate measurement was approximately 1 min. The particles measured by the tester were airborne particles of more than 0.5 μm in diameter. During the measurement, incense sticks were burned to keep the particle concentration in the artificial climate chamber above 1,000 counts/3 s, which is recommended by the MT-03 manufacturer. The concentration inside the RPE was measured by sampling the air inside the facepiece using a tube joint set fixed to the sampling tube and the RPE. When measuring the concentration outside the PRE, the sampling tube was suspended from the ceiling and fixed so that its inlet was close to the RPE.

Calculating the fit factor

According to JIS T8150[10] or the fit testing procedure prescribed by OSHA[9], the fit factor was calculated by dividing the concentration inside the particulate respirator (Ni) by the concentration outside (No):

$$Fit\ factor = \frac{Number\ of\ test\ exercises}{Ni_1 1/No_1 + Ni_2/No_2 + Ni_3/No_3 + Ni_4/No_4 + Ni_5/No_5}$$

Numbers 1 to 5 represent test exercises 1–5.

OSHA states that test participants should not be permitted to wear a half mask or quarter facepiece respirator unless a minimum fit factor of 100 is secured.[9] Thus, in this study, we used fit factor ≥100 as an indicator that respiratory protection was maintained.

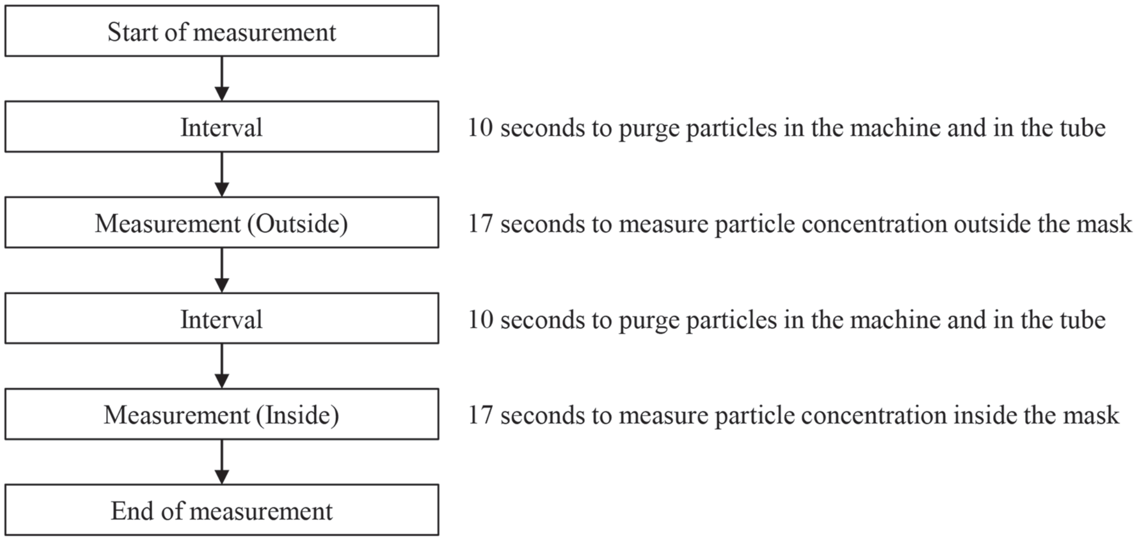

Fig. 3. Outline of the mask-fit test procedure.

Variables

The outcome variable was fit factor, and the predictor variables were physical state (resting state or exercise state) and wearing variation. We adjusted for sex as a confounding factor.

Statistical methods

Data were analyzed after they were log-transformed with a linear mixed model (LMM), with fit factor as the dependent variable. Among the independent variables, the random factor was the survey participants, and the fixed factors were the gender of the participants, physical state, wearing variation, and the interaction between physical states and wearing variations. The Bonferroni method was used for multiple comparisons[11]. The estimated marginal means (EMM) by physical state or wearing variation were calculated by adjusting for the dependent variable in the LMM. All statistical analyses were performed using the IBM SPSS Statistics 23.0. The significance level was set at p<0.05.

Ethical approval

The Ethics and Informed Consent Procedure for this study was approved by the Ethics Committee of Medical Research, University of Occupational and Environmental Health, Japan (Receipt No. H30-58). Informed consent was obtained from all participants.

Results

Fit factor for each physical state and wearing variation

Table 1 shows the number of cases with fit factor ≥100 and the mean [SD] fit factor value for each physical condition and wearing variation.

No cases of fit factor ≥100 were observed for the RPR_K wearing variation. The number of cases with fit factor ≥100 was higher when the PAPR was worn compared to when the RPR was worn both at rest and during exercise. A fit factor ≥100 was observed for each of the three PAPR wearing variations in the resting state, and only one in ten cases had fit factor <100 when the PAPR was worn during exercise. The mean values of fit factor were also higher when the PAPR was worn than when the RPR was worn, and at rest than during exercise.

Comparison of fit factor by physical state and wearing variation

Table 2 shows the results of the statistical comparison of fit factor by physical state and wearing variation. We analyzed the interaction between the physical states and wearing variations. The fit factor was significantly lower when the RPE was worn in during exercise than when it was worn at rest. The fit factor was statistically significantly minimum among all wearing variations when RPE was worn by RPR_K. Following RPR_K, when fitted using RPR_R and RPR_H, the fit factor was significantly lower than when the PAPR was worn. The fit factor was significantly highest when the PAPR was worn. No sig-

Table 1. Number of cases with fit factor >100 and the mean (standard deviation) fit factor for each physical condition and wearing variation

Wearing variation	Fit factor (FF)					
	Resting state			Exercise sate		
	# with FF ≥100	M[f]	SD[g]	# with FF ≥100	M	SD
RPR_H	3	118.7	(111.8)	2	68.2	(55.4)
RPR_K	0	12.3	(5.5)	0	9.3	(4.7)
RPR_R	4	145.3	(141.1)	3	84.8	(75.6)
PAPR_H	10	737.2	(408.8)	9	468.7	(284.3)
PAPR_K	10	762.4	(357)	9	396.6	(282)
PAPR_R	10	786.5	(375.7)	9	444.5	(326.9)

with FF ≥ 100: number of participants with fit factor ≥ 100.
RPR: replaceable particulate respirators; PAPR: powered air purifying respirator; M: mean; SD: standard deviation.

Table 2. Comparison of fit factor values among physical states and wearing variations

Variable		Ln (FF value)		
		EMM	95% CI	*p*
PS	Rest	5.13	[4.54–5.71]	<0.001
	Exercise	4.62	[4.04–5.21]	
WV	RPR_H	4.14	[3.53–4.75]	<0.001
	RPR_K	2.29	[1.67–2.90]	
	RPR_R	4.29	[3.68–4.90]	
	PAPR_H	6.20	[5.59–6.81]	
	PAPR_K	6.13	[5.52–6.74]	
	PAPR_R	6.22	[5.61–6.83]	
Interaction between PS and WV				0.795

We represented each wearing variation by combining "RPR" or "PAPR" with "wearing method." For example, a PAPR worn according to the recommended method (R) is represented as PAPR_R.
Post-hoc test: RPR_K<RPR_H/R<PAPR_H/K/R.
FF: fit factor; PS: physical status; WV: wearing variation; EMM: estimated marginal mean; CI: confidence interval; Ln: natural logarithm; RPR: replaceable particulate respirators; PAPR: powered air purifying respirator.

nificant difference in fit factor values was observed when the PAPR was worn by PAPR_H, PAPR_K, and PAPR_R. There was no significant interaction between physical state and wearing variation.

Discussion

We measured the fit factor of an RPR and PAPR under three different wearing variations during exercise. The fit factor of the RPR and PAPR during exercise was significantly lower than and about half that measured at rest. This may be because the adhesion between the face and the RPE tends to decrease during exercise tasks. There was no significant interaction between the physical states (resting and exercising) and wearing variations. Our findings suggest that even when workers wear RPE properly, working reduces respiratory protection.

The fit factor of the PAPR used during exercise was greater than 100 in 9 of 10 cases for all wearing variations. In contrast, the fit factor of the RPR during exercise was greater than 100 in only three cases using the recommended wearing method. There were no cases in which the fit factor was greater than 100 when a knit cover was worn with the RPR. Since the inside of the PAPR is constantly kept under positive pressure, the performance of the PAPR would not have declined even if exercise impaired the adhesion between the PAPR and the face. While it is clear that PAPRs are superior to RPRs in terms of respiratory protection, they are reportedly rarely used in the workplace because of their price and size[5)], and most workers complain about their heaviness[12)]. These reasons may hinder the use of PAPR.

The mean fit factor when a knit cover was worn with RPRs was 12.3 at rest and 9.3 during exercise, with both values being significantly lowest among all wearing variations. The fit factor was less than 100 for all participants, which suggests that the knit cover compromised the adhesion between the face and the RPR. When wearing a knit cover with PAPRs, the fit factor was greater than 100 even during exercise, indicating that respiratory protection was maintained. If there is a risk that wearing RPE can cause eczema or other skin problems, workers are allowed to use a knit cover as long as good adhesion is ensured[4)]. Since this study showed that wearing a knit cover impairs adhesion of the RPR to the face, we recommend that workers with skin disorders select PAPR when using a knit cover.

There was no significant difference in fit factor between the recommended method of wearing the RPR and RPR over a helmet. In this study, we adjusted each participant's tightening strap so that their RPR was attached to their face with the adequate pressure. In the field, however, there may be individual differences in how RPR are worn and fitted. Further, the RPR, PAPR, and helmet we examined were all the same model and brand new. Thus, while the RPE headband fit well over the helmet in our study, it is unclear whether the results would be similar for other models. It is also unclear how aging of the RPR or helmet affects the fit of the headband and helmet. Further study is needed to clarify these points before we can recommend wearing RPE over a helmet. However, many workers in the workplace reportedly wear RPE over their helmets[5]. Working in a dusty environment while wearing RPE with a poorly adherent attachment does not sufficiently prevent pneumoconiosis. It is important to provide continuous education and guidance to workers to ensure that they wear RPE with minimal leakage. In Japan, fit testing has only recently been made mandatory; from April 2023, fit testing will be mandatory for workers who perform welding work. The fit test is expected to lead to more appropriate wearing of masks.

Recently, the concept of workplace protection factor (WPF) has emerged with the increasing awareness of the importance of evaluating RPE protection in the workplace. WPF is a measure of the protection provided in the workplace when a properly functioning respirator is correctly fitted and used[13], and several studies have been published on WPF[14–18]. In this study, respiratory protection during exercise tasks was evaluated in an artificial climate chamber. We have also conducted experiments to measure WPF using the mask-fit tester adopted in this study and reported on the differences in WPF by type of RPE and wearing method[19]. Given that there are few reports on WPF measurement in Japan, further research is needed to determine the most appropriate use of RPE in actual workplaces.

This study has some limitations. First, the number of participants was small, and there may have been a large number of type 2 errors (i.e., differences that should have been there that may not have been recognized). Further validation with a larger number of participants is needed to examine differences by face size and the influence of gender. Second, the RPRs, PAPRs, knit cover, and helmet we used were of only one type. Verification of our results with multiple types of RPE is warranted. Moreover, the RPE, knit cover, and helmet used were brand new. In workplaces, as workers use the same equipment over and over again, deterioration of the silicone of the RPE, knit cover, and helmet may affect the fit factor. Third, the participants may have been more rigorous about how they wore the RPE than actual workers. To minimize the effect of each individual's ability to accurately fit the RPE, the participants put on their RPE while looking in a mirror. If the examiner noticed signs of improper fitting, such as a twisted strap, the participant was asked to remove the RPE and re-attach it. Verification of WPF in actual workers without any advice on how to wear the RPE is a subject for future study.

Conclusion

We evaluated the respiratory protection of RPRs and PAPRs during exercise tasks under various wearing methods. The fit factor of RPRs during exercise was significantly lower than and about half that at rest, indicating inadequate respiratory protection. On the other hand, the fit factor of PAPRs was also significantly lower than and about half that at rest, but respiratory protection was maintained. PAPRs are thus more suitable than RPR for a worker who cannot wear RPE appropriately due to health issues.

Author Contributions

HB: interpretation of data and drafting the article. HA and KI: acquisition of data, analysis and interpretation of data, drafting the article. SS: reviewing and editing the article. TS: acquisition of data, analysis and interpretation of data. AO: oversight and taking leadership responsibility for the planning and execution of all research activity. All authors critically revised and approved the final manuscript.

Funding

This study was funded by Industrial Disease Clinical Research Grants (No. 180302-01).

Conflict of Interest

The authors declare no conflicts of interest.

Acknowledgements

We would like to thank Ms. Saki Nakase of the Shared-Use Research Center, University of Occupational and Environmental Health, Japan for her technical support and advice. We would also like to thank DMC Corp. (https://dmed.co.jp/) for editing a draft of this manuscript.

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