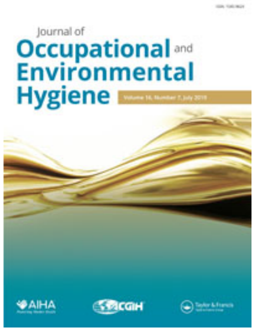

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REPORT

A pilot study of minimum operational flow for loose-fitting powered air-purifying respirators used in healthcare cleaning services

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ABSTRACT

The objective of this pilot study was to determine the minimum operational flow for loose-fitting powered air-purifying respirators (PAPR) used in healthcare cleaning services. An innovative respiratory flow recording device was worn by nine healthcare workers to obtain the minute volume (MV, L/min), mean inhalation flow (MIF, L/min), and peak inhalation flow (PIF, L/min) while performing "isolation unit work" (cleaning and disinfecting) of a patient room within 30 min. The MV and PIF were compared with the theoretical values obtained from an empirical formula. The correlations of MV, MIF, and PIF with subjects' age, weight, height, body surface area (A_{Du}), and body mass index (BMI) were analyzed. The average MV, MIF, and PIF were 33, 74, and 107 L/min, with maximal airflow rates of 41, 97, and 145 L/min, respectively, which are all below the current 170 L/min minimum operational flow for NIOSH certified loose-fitting PAPRs.

KEYWORDS

Healthcare workers; minimum operational flow; minute volume; peak inhalation flow; powered air-purifying respirators; respiratory flow

Introduction

There is a high risk of occupational exposure for healthcare workers (HCWs) to influenza, viruses, bacterial pathogens, and emerging diseases.[1–3] During the outbreak of severe acute respiratory syndrome (SARS) in 2003, HCWs were reported to account for 20% of critically ill SARS cases.[4] The 2009 H1N1 influenza pandemic and the recent Ebola outbreak have further amplified the concerns of HCWs for adequate respiratory protection equipment (RPE). The most common RPE used by HCWs are surgical masks and National Institute for Occupational Safety and Health (NIOSH)-approved N95 filtering facepiece respirators (FFRs).[5,6] However, surgical masks are not able to provide barrier to sub-micrometer-size bioaerosols,[7,8] while N95 class filters are associated with high breathing resistance, which may be the reason for 1/3 of HCWs' headaches during long-term use of N95 FFRs.[9] In addition, annual fit-testing is required for N95 FFRs since face seal leakage would significantly affect the achieved protection.[10,11]

The finding that HCWs were infected with SARS despite the use of N95 FFRs gave rise to the interest in using powered air-purifying respirators (PAPR) for outbreaks of highly contagious pathogens.[12,13] The Occupational Safety and Health Administration (OSHA) defines a PAPR as "an air-purifying respirator that uses a blower to force the ambient air through air-purifying elements to the inlet covering."[14] Compared to N95 FFRs, PAPRs feature several advantages to the wearers. Firstly, PAPRs offer higher assigned protection factors (APF) ranging from 25 (loose-fitting PAPRs) to 1,000 (full facepiece tight-fitting PAPRs), whereas the APF for N95 FFRs is 10.[14] Other significant advantages of using PAPRs are the decreased breathing effort and the cooling effect on the face. In addition, loose-fitting PAPRs do not require annual fit-testing and can be used by HCWs who cannot achieve a good fit with N95 FFRs due to facial hair or other factors.[15]

Given that a loose-fitting PAPR is not designed to completely seal to the face or neck, if inspiratory flow exceeds the airflow delivered by the blower (over breathing), unfiltered air may leak in.[16] It was found that with increasing inspiratory flow, the manikin fit factors

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for a loose-fitting PAPR decreased exponentially.[17] Therefore, the determination of minimum operational flow is crucial for a loose-fitting PAPR. PAPRs were originally developed to protect various industrial workers from workplace airborne hazards.[3] The minimum air flow rates for NIOSH-approved tight-fitting and loose-fitting PAPRs are 115 L/min and 170 L/min, respectively.[14] These testing flow rates were mainly obtained from industrial workplaces, primarily mining.[18,19] Industrial settings often require workers to perform moderate to high effort job activities,[20] therefore PAPRs used in those conditions must provide sufficient air flows to satisfy the breathing demands for the workers. However, the workplace environments experienced by HCWs differ significantly from the industrial conditions, especially pertaining to physical exertion when performing routine work activities.[21]

Currently, there are no scientific studies conducted on the respiratory flow required by HCWs using PAPRs, and no national or international standards are available regarding the minimum operational flow for PAPRs used by HCWs. The objective of this pilot study was to investigate the breathing characteristics of one group of HCWs (hospital cleaning staff) in order to determine the minimum operational flow required for operating loose-fitting PAPRs. The methods developed in this pilot study can be easily used to characterize breathing flow for all other HCW groups. The results obtained from this study may assist in improving the scientific basis for future updates to NIOSH PAPR standards.

Methods

Instrumentation

An innovative portable respiratory flow recording device (Safety Equipment Australia [SEA] Pty Ltd., Australia) was employed in this field study. The device features a compact design (<0.5 kg) and can be worn by a worker without significant interference with the routine job tasks. The device consists of a data logger, a pressure sensor and a breathing mask (available size options: Small/Medium, Medium/Large, and Large/Extra Large). The differential pressure sensor is mounted inside the mask to measure breathing resistance/pressure drop ($\triangle P$). A reading is taken every 0.02 sec and stored in the data logger, which can be belt or pocket mounted. The battery capacity allows sampling for at least a full 8-hr work shift. After sampling, each reading of $\triangle P$ is converted into a respiratory flow rate through a pre-calibrated $\triangle P$-flow curve. The maximum flow measurement for the device is 400–500 L/min.

Table 1. Test subject physical characteristics.

Subject	Gender	Age	Weight, kg	Height, m	A_{Du}, m^2	BMI, kg/m^2
#1	M	43	117.93	1.65	2.21	43.27
#2	F	39	86.18	1.63	1.91	32.61
#3	F	21	113.4	1.65	2.17	41.60
#4	F	44	65.77	1.50	1.60	29.29
#5	F	45	56.70	1.65	1.62	20.80
#6	M	43	61.24	1.60	1.63	23.91
#7	F	28	58.97	1.60	1.61	23.03
#8	F	49	60.33	1.60	1.62	23.56
#9	F	22	68.04	1.65	1.75	24.96

Experimental set-up

Through our investigation on HCWs' previous experience wearing PAPRs, the "isolation unit work," which included thorough cleaning and disinfecting of a patient room with possible airborne infectious diseases, was identified as a physically demanding task with a risk of infectious exposure. Each "isolation unit work" was required to be completed in 30 min. One HCW would clean up to 12 units per day.

A group of nine HCWs was recruited from the Environmental Services Department, Monongahela General Hospital, Morgantown, WV. Internal Review Board (IRB) approval was obtained through the West Virginia University (WVU) and the Monongahela General Hospital prior to subject recruitment. Test subjects signed a consent form and a photo release. Physical measurements of the subjects are summarized in Table 1.

Each subject wore the respiratory flow recording device while performing the "isolation unit work" (Figure 1). Inspiratory flow rates were recorded in real time (50 Hz) for each task. A summary of experimental conditions is listed in Table 2. Sampling time for each subject was adjusted depending on the completion of the "isolation unit work."

Data analysis

All data were corrected to BTPS (Body Temperature Pressure Saturated). The minute volume (MV, L/min), mean inhalation flow (MIF, L/min), and peak inhalation flow (PIF, L/min) (Table 3) were reported and analyzed. The MV and PIF were compared with the theoretical values obtained from the empirical formula as described in detail in ISO/TS 16976-1:2015.[20] The Pearson product-moment correlation coefficient was calculated. The correlations of MV, MIF and PIF with subjects' age, weight, height, body surface area (A_{Du}), and body mass index (BMI) were analyzed. All data analyses were performed with SAS version 9.3 (SAS Institute Inc., Cary, NC). P-values < 0.05 were considered significant.

Figure 1. Subject wearing respiratory flow recording device while performing the "isolation unit work" (photo credit: WVU).

Table 2. Summary of experimental conditions.

Variable	Level
Device	A portable respiratory flow recording device
Subject	9 HCWs from Monongahela General Hospital, Morgantown, WV
Isolation Unit Work (within 30 min)	1. Empty waste—empty waste and change trash bags
	2. High dust—use a duster to clean the dust in high places
	3. Sanitize—sanitize everywhere of the unit
	4. Spot clean—clean bed, chair, wall, window, door, etc.
	5. Clean restroom—clean stool, washbasin, bathtub, etc.
	6. Dust mop—use a dry mop to clean the floor
	7. Inspect work—inspect if anywhere need re-clean
	8. Damp mop—use a wet mop to clean the floor

Table 3. Definitions of inspiratory flows.

Inspiratory Flow	Definition
MV	Air volume inhaled in 1 min, L/min
MIF	Mean flow rate during inhalation phase, L/min
PIF	Average of peak inhalation flow rates of a series of breath cycles, L/min

Note: MV was directly measured by the device; MIF was calculated as MV divided by inhalation time; PIF was calculated as the average value of peak inhalation flow rates during a series of breath cycles.

Results and discussion

It should be noted that the eight exercises listed in Table 2 were based on standard procedure set by the hospital for the "isolation unit work"; however, during actual working process, the workers may not fully obey this procedure. Some of the exercises may be omitted, while other exercises (e.g., changing curtain, Figure 1) may be added. Since this is a field investigation in real hospital patient rooms, observers were not allowed to step inside to visually determine the exact time period of each exercise. Furthermore, for all nine subjects tested, it was found that the change of MV, MIF, and PIF during the 30-min "isolation unit work" was minimal. Therefore, data analyses were performed for the entire 30-min "isolation unit work". The minimum, average ± standard deviation (SD), and maximum values of the MV, MIF, and PIF for the nine HCWs were reported (Table 4).

As defined in ISO/TS 16976-1:2015, the estimated average MV values for small, medium, and large sized people (A_{Du}=1.69, 1.84, and 2.11 m^2, respectively) performing moderate workload tasks were 33, 36, and 41 L/min, respectively.[20] Since most subjects in this study were small/medium sizes (Table 1), and the average MV was 33 L/min, with the range of 22–41 L/min, it was concluded that the "isolation unit work"

Table 4. Inspiratory flows (L/min) during the isolation unit work.

Inspiratory Flow	Minimal value	Mean ± SD	Maximal value
MV	21.7	32.5 ± 5.2	41.4
MIF	52.7	74.2 ± 12.6	97.1
PIF	76.4	106.8 ± 17.2	145.3

Table 5. Theoretical MV and PIF under speech and non-speech conditions, all in L/min.

Speech Condition	Parameter	Minimal value	Mean ± SD	Maximal value
Non-speech	MV	31.5	35.1 ± 4.6	43.3
	PIF	99.0	108.3 ± 11.6	129.0
Speech	MV	25.2	28.1 ± 3.6	34.6
	PIF	200.1	211.5 ± 14.1	236.6

(generally more physical demanding compared to other healthcare job activities) could be classified as a moderate workload task. The range for MIF was reported as 53–97 L/min. The average PIF was found to be 107 L/min, with the maximum airflow of 145 L/min (lower than the flow required for the NIOSH-approved loose-fitting PAPRs of 170 L/min).

According to the physical characteristics of subjects in Table 1 and the metabolic rate of the "isolation unit work" (moderate workload = 165 W/m^2), the empirical formula listed in ISO/TS 16976-1:2015[20] was applied to estimate the theoretical MV and PIF values for HCWs under both speech and non-speech conditions, as presented in Table 5.

It was found that there was no significant difference between the theoretically calculated MV and PIF under the non-speech condition (Table 5) and the corresponding measured values (Table 4). However, the estimated MV and PIF under the speech condition (Table 5) were significantly different from the measured values (Table 4). Therefore, it was concluded that the "isolation unit work" is very close to a non-speech condition. Based on moderate workload and subjects' physical characteristics, the inspiratory flow of HCWs when performing "isolation unit work" can be mathematically computed by the empirical formula listed in ISO/TS 16976-1:2015.[20]

Other HCWs, such as nurses and doctors, might talk much more than the workers involved in this study. Prior to this study, another laboratory-based investigation on the PIF including one exercise of "patient assessment–asking questions" (speaking while standing) was performed.[23] Each test ran 1 min and was repeated three times. Fifteen human subjects were recruited. Subjects' age, weight, and height were 27.3 ± 3.9 years, 69.8 ± 12.9 kg, and 171.7 ± 10.5 cm (means ± standard deviation), respectively. It was found that the PIF during speech was 96 ± 17 L/min

Table 6. Pearson correlations of MV, MIF, and PIF with age, weight, height, A_{Du}, and BMI.

	Coefficient of Correlation		
Variable	MV	MIF	PIF
Age (years)	−0.05	−0.27	−0.08
Weight (kg)	**0.69***	**0.80***	**0.74***
Height (m)	0.21	0.28	0.00
A_{Du} (m^2)	**0.67***	**0.79***	**0.68***
BMI (kg/m^2)	**0.69***	**0.79***	**0.78***

Note:
*Suggests coefficient of correlation is significant ($P < 0.05$).

with a maximum rate of 127 L/min for all subjects, which is not greater than the PIF reported in the process of the "isolation unit work."

The relationship between inspiratory flow rates and subjects' physical characteristics was investigated, and the correlation results of MV, MIF, and PIF with age, weight, height, A_{Du}, and BMI are shown in Table 6. The Pearson correlations of MV, MIF and PIF with weight, A_{Du} and BMI were all positive and statistically significant. Since both A_{Du} and BMI are expressions of weight and height,[20,22] and height was not statistically significant (may be caused by its narrow range: 1.50–1.65 m), the results suggest that weight has a significant effect on subjects' inspiratory flow. As the subjects' weight increased, the inspiratory flow increased significantly. The correlations of MV, MIF, and PIF with age were negative, indicating that with the increase of age, inspiratory flow tends to decrease, although this decrement was not statistically significant.

There are some limitations in this study. Firstly, only nine HCWs were recruited, most of whom are smaller than average (6/9 weigh less than 70 kg; height 1.50–1.65 m). Secondly, only one group of HCWs from the hospital's Environmental Services Department was investigated. Finally, only healthy workers were investigated. To fully understand the inspiratory flow characteristics of HCWs, more workers with different physical characteristics/conditions from different departments need to be investigated.

Conclusion

The "isolation unit work" (a more physical demanding work in healthcare) qualifies as a moderate workload activity. Correlation analysis showed that as the weight of the HCWs increased, the inhalation flow increased significantly. The MV, MIF, and PIF during the "isolation unit work" were 33, 74, and 107 L/min, with maximum airflow of 41, 97, and 145 L/min, respectively, which were all lower than the 170 L/min minimum operational flow required for NIOSH approved loose-fitting PAPRs. The methods developed in this pilot study can be used to characterize breathing flow for all other HCW groups.

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