

Breathing Recording Aimed to Provide Appropriate Test Flow Rate on Performance Evaluation of Respirators for Elementary School Children

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ABSTRACT

Against the background of concerns over health problems such as the bird flu pandemic and PM_{2.5} air pollution in Japan, there is increasing interest in the development of respirators for elementary school children that provide the same level of protection as respirators for adults. The respiratory volumes of respirator wearers have a major effect on respirator performance, and vary significantly depending on the wearer's physique and level of activity. To facilitate the creation of a protocol for the evaluation of respirator for elementary school children, we recorded breathing patterns under conditions that simulate their daily activities at school. Two types of breathing recording masks were used to accommodate a wide range of facial characteristics. These masks can record breathing patterns by measuring the changes in air pressure generated by breathing. Twenty-one elementary school children ranging from grade 1 to 6 participated in this study. Breathing patterns and heart rates were recorded while the subjects performed five exercises: (1) Sitting, (2) Writing on a blackboard, (3) Stepping, (4) Carrying a school chair, and (5) Running. The average exercise intensity, as derived from heart rates, increased from 7 to 54 %HRR as the activity level increased. Similarly, average respiratory inhalation minute volumes and peak flow rates increased from 8 to 21 L min⁻¹, and from 27 to 65 L min⁻¹ respectively. Moreover, the peak flow rate at a light exertion level, which is the condition under which children are expected to use respirator, was 60.6 L min⁻¹. Consequently, a test flow rate of approximately 60 L min⁻¹ may be appropriate for the performance evaluation of respirators for respiratory protection in children.

Keywords: Elementary school children, Breathing pattern, Heart rate, Exercise intensity, Dust mask.

INTRODUCTION

Face masks are commonly used in Japan to avoid inhaling allergens and pollutants, or to prevent disease transmission. Recently, because they have been encouraged as a measure to prevent the inhalation of flu virus-containing droplets and hazardous ambient particles such as PM_{2.5}, their efficacy has come under scrutiny. PM_{2.5} is much smaller than cedar pollen (about 30 μm), and can thus penetrate deeper into the lungs and cause serious health problems. Dockery et al. (1993) reported that cardiopulmonary mortality has a positive correlation with PM_{2.5} concentration. There is a rapidly growing demand for high performance masks aimed at respiratory protection. In this respect, respiratory protection for children presents a more important issue than for adults, because children have larger respiratory volumes per kilogram of body weight (Bureau of Social Welfare and Public Health, 2011; United States Environmental Protection Agency, 2011); i.e., children are more susceptible to harmful inhaled substances. Seo et al. (2016) described the necessity of developing respirators for children against this issue in their published paper which related to survey on facial characteristics for Korean children to use baseline data in future for masks for children. Accordingly, the Japanese Ministry of Education, Culture, Sports and Technology has mandated that school health programs take into account the fact that there are many children with allergies in elementary schools (Japanese Ministry of Education, Culture, Sports and Technology, 2007). Moreover, because the principal infection routes of bioagents such as influenza viruses are the contact, droplet, and airborne routes, children are at an extremely high risk for infection because of the daily conditions in school. Thus, it is recommended that respirators for children, who are inherently more vulnerable to infection than adults, should have high performance specifications with respect to respiratory protection. Unfortunately, most commercially available respirators are designed for adult use only. In fact, poor fit factors were observed when elementary school children wore respirators, allowing many particles to pass through the gap between face and facepiece (Tuda, 2011). Furthermore, the difference in relative respiratory volume significantly reduces the efficiency of filtering hazardous particles.

Although manufacturers do list various performance specifications, it is difficult to know the actual effectiveness of face masks regarding respiratory protection (National Consumer Affairs center of Japan, 2009). In recent years, the N95 filtering facepiece respirators (FFRs) have become well known as high performance respirators for professional use among the Japanese people. N95 FFRs meet the standards defined by the U.S. Federal Government (Federal Register, 1995) and are approved by the National Institute for Occupational Safety and Health (NIOSH). Normally, N95 FFRs are used to provide respiratory protection for workers in hazardous environments, or for infection control for health care workers, as seen during the severe acute respiratory syndrome outbreak in 2003 (Rubinson, et al., 2005; Roberge, 2008). In Japan, "dust masks," which are equivalent to N95 FFRs, are used in such work environments. The standards and performance criteria for dust masks are defined in the national standards of the Health Labor and Welfare Ministry in Japan (Health, Labor and Welfare Ministry, 1988).

These standards can be used as a reference from which to design and develop a test protocol for children's respirators, considering the differences in breathing volume and usage conditions. However, in order to do this, we first require a reliable means of measuring breathing parameters in children under conditions that simulate their daily activities. A novel method using a breathing recording mask for respirator wearers has been used to survey breathing patterns that significantly affect respirator performance. Measurements of breathing volume, breath frequency, and peak flow rate can be obtained via this method (Yuasa et al., 2008; Anderson et al., 2006; Grinshpun et al., 2009).

To our knowledge, this technique has not yet been validated in elementary school children. Therefore, to assess the reliability of this method and to acquire data that would be useful for designing respirators for children, we carried out breathing recording in a group of elementary school children under conditions that simulate their daily activities in school.

METHODS AND MATERIALS

Subjects

Twenty-one healthy children participated in this study, with their parents' consent. The study design was approved by the Koken institutional review board, which includes a medical doctor. The study population was composed of elementary school children between 6 and 12 years of age, with 11 boys and 10 girls. The average body surface areas, as an index of physique, for the early elementary subjects (grade 1 to 3, including 6 boys and 5 girls), the late elementary subjects (grade 4 to 6, including 5 boys and 5 girls), and the total study group were 0.9, 1.11, and 1.00 m², respectively.

Breathing Recording Mask

The method used for breathing recording mask in this study was based on that reported by Yuasa et al. (2007). A small pressure sensor incorporated in the facepiece digitally logs the changes in pressure inside the facepiece as the subject inhales and exhales, and the data are converted to breathing flow rates using calibration curves. The calibration curves were prepared by measuring the relationship between pressure changes inside the facepiece and flow rate.

As previously reported (Haruta et al., 2011), the fit between the face and facepiece is important in order for the breathing recording mask to function properly. A poor fit adversely affects accuracy because air leakage through the gap causes the measurements of facepiece pressure to be inaccurate. For this reason, two types of masks were used to accommodate a wide range of facial dimensions. Type A (Figure 1) was a filtering facepiece with a three-dimensionally curved facepiece lip designed to fit children's faces, while Type B (Figure 2) was a tight-fitting mask with an elastomeric facepiece (silicone rubber), which is used as an 'escape mask' for children in Japan. Each mask was equipped with elastic head straps that could be adjusted to fit each child's face shape and head size. After an N95-rated filter, which has sufficient filtration performance against ambient aerosols in a normal environment, was attached to the masks, the fit of the masks was confirmed by a quantitative fit test.

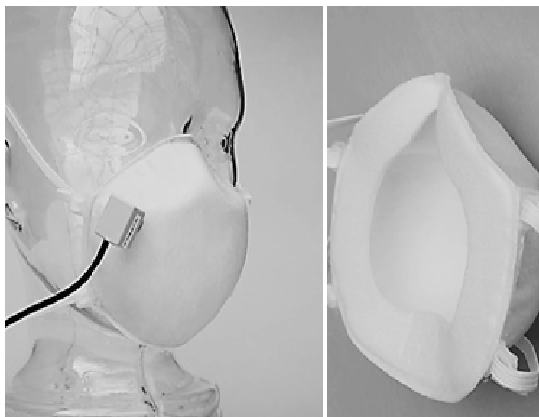


Figure 1. Breathing recording mask (Type A)



Figure 2. Breathing recording mask (Type B)

Protocol of Breathing Recording and Test Activity

The breathing recording measurements were conducted in a room about the same size as a common school classroom. The participants and their guardians were provided with an explanation of the aim and contents of the test, and then provided informed consent. The age, weight, and height of each

subject were obtained via questionnaire and confirmed by their guardians. After the questionnaire, the subjects were given small wearable heart rate meters (RS800CX, Polar, Finland) to estimate their level of physical activity during the test.

As described earlier, two types of breathing recording masks were prepared. For each mask, the total inward leakage was measured as a ratio of the ambient aerosol concentrations measured inside (C_i) and outside (C_o) the mask with the mask fitting tester (MT-03, Shibata Scientific Technology LTD., Japan) in order to confirm the fit between face and facepiece. The total inward leakage was calculated using the following equation (1),

$$\text{Total inward leakage (\%)} = 100 \times \frac{C_i}{C_o} \cdots (1)$$

The total inward leakage of the Type A mask was tested first. If it exceeded 1.0%, the subject was given the Type B mask and the leakage was measured again. Whichever mask provided a better fit was selected for the breathing recording.

Five test exercises were used to simulate the daily activities in school (Table I). Each exercise was carried out for 3 minutes. For the first exercise of sedentary, the subjects sat on a chair in a relaxed manner. For the second exercise, the subjects either wrote a list of Chinese characters or performed math calculations on a blackboard while standing. In the third activity, the subjects were given a set of step exercises: a step height of 15 cm and a stepping rate of 15 steps min^{-1} . The oxygen consumption for this exercise can be calculated by a formula provided by the American College of Sports Medicine (ACSM, 2000). For example, when a 10-year-old boy with an average body size performs the stepping exercise under these conditions, his percentage of required oxygen consumption as a function of the maximum oxygen consumption ($\% \text{VO}_{2\text{max}}$) can be estimated as 28% based on the population average (The Tokyo Metropolitan University physical strength standard value workshop, 2000; Ministry of Education, Culture, Sports, Science and Technology, 2012). This exercise intensity corresponds to a walking speed of 5 km h^{-1} on level ground (ACSM, 2000).

Table I. Test Exercise Simulating Daily Activity in School Used in Breathing Recording Test

Test exercise		Condition
①	Sedentary	Sitting on a chair
②	Writing on Blackboard	Standing
③	Stepping	15cm×15 steps min^{-1}
④	Carrying a school chair	Arbitrary pace
⑤	Running	Arbitrary pace

The fourth and fifth exercises, carrying a school chair and running, respectively, were performed at an arbitrary pace chosen by the subject. Measurements of heart rate and breathing pattern were monitored in real time using wireless communication. For all exercises, recording was started after the measured data showed stable values.

Calculating Breathing Data and Exercise Intensity

Because the main function of respirators is to prevent the inhalation of hazardous particles, we only analyzed the data during inspiration. All values are presented as an average of the data recorded during the 3-minute activities.

Figure 3 shows a representative image of the data output. Inhalation minute volume (MV: L min⁻¹) is the volume of inspiratory airflow per minute, and all data points of inspiratory flow rate were summed and averaged over the sampling period. Mean peak inspiratory flow rate (PIF: L min⁻¹) is the average of all the maximum inspiratory flow rates in each individual breath cycle, which is represented by a broken circle in the figure. Breathing frequency (F: cycles min⁻¹) is the number of the individual breathing cycles per minute. Mean tidal volume ($\bar{V}_T$: L) is the average of all the inspiratory volumes in the individual breathing cycles, represented by the shaded areas in the figure. Mean breathing cycle time ($\bar{T}_{tot}$: sec) is the average of the individual breathing cycle duration between inhalation and exhalation. Mean inspiratory time ($\bar{T}_I$: sec) is the average of inspiratory duration in each breathing cycle.

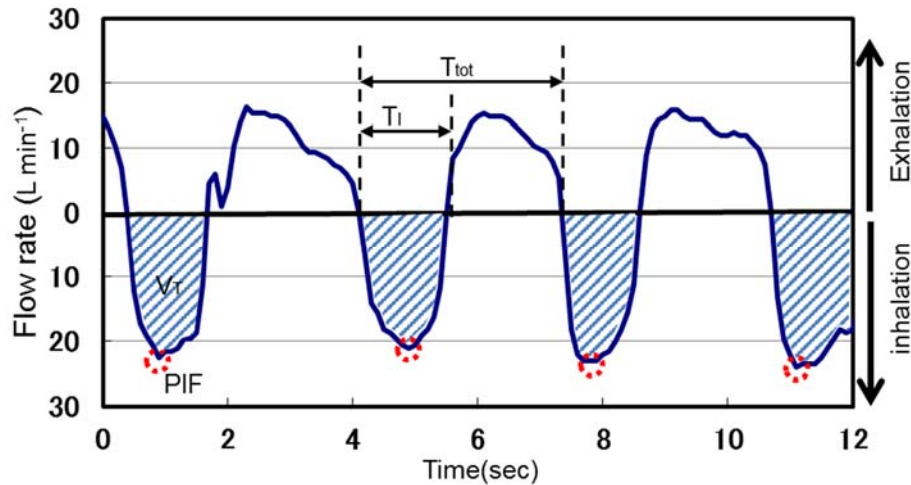


Figure 3. Illustration of the breathing data obtained from breathing pattern

Heart rates for each subject were also measured continuously during each test period and averaged. An exercise intensity calculated as a percentage of maximum oxygen consumption (%VO₂max) can be estimated in an alternative fashion by the equation (2) using reserved heart rate data (Physical education scientific center, 1983).

$$\%VO_2 \text{ max} = \%HRR = \frac{\text{heart rate during exercise} - \text{heart rate at rest}}{\text{maximum heart rate} - \text{heart rate at rest}} \times 100 \dots (2)$$

Thus, an estimated exercise intensity ($\overline{\%HRR}$) was calculated for each test activity. Because of the difficulty of acquiring stable measurements of resting and maximum heart rates for children, we used reference values according to the subjects' age (Akiyama T, 2011; Himaru, 1991).

RESULTS AND DISCUSSION

Fit of Breathing Recording Mask for School Children

Table II shows the measurements of total inward leakage according to the subjects' age. In these fit tests, even when a high leakage value ($> 1.0\%$) was observed at the first trial, almost all subjects were able to improve the fit by adjusting the head straps accordingly.

Table II. Total Inward Leakage (%) for Each Test Subject by Type A and B Masks

Age	A type	B type
6	2.09	0.44
7	0.30	-
7	1.17	0.42
7	0.89	-
7	1.52	0.60
7	2.29	0.46
8	0.02	-
8	0.33	-
8	0.37	-
9	0.58	-
9	0.98	-
10	0.24	-
10	0.34	-
10	0.39	-
10	0.81	-
10	0.81	-
10	0.98	-
11	0.13	-
11	0.26	-
12	0.53	-
12	0.85	-

Consequently, 17 of 21 subjects achieved a leakage rate of below 1.0% with the Type A mask, while the other four achieved the same with the Type B mask. As described previously, the fit of the mask significantly affects the measurement accuracy. The measurements of total inward leakage in our subjects were satisfactorily low, even when compared with the results of similar fit tests in adult medical workers with N95 respirators (Kurosu et al., 2008; Chiba, 2010). Additionally, we have previously found that the

accuracy of this breathing recording method is not adversely affected as long as the inward leakage is <3.0% (Yuasa et al., 2007). Therefore, the masks used in the current study were able to provide an adequate fit, which is necessary for recording the subjects' breathing patterns accurately.

Breathing Data of Child Subject at Each Test Activity

Table III shows descriptive statistics of the means and standard deviations of the breathing data and estimated exercise intensity for each test exercise. The estimated exercise intensity (%HRR) increased progressively from 7% for the sedentary activities to 54% while running. Based on the population mean values of %HRR, physical activity levels are classified into four categories (Japan Sports Council, 2007): "daily activity" (from 0 to 30%), "light exertion in daily activity" (from 30 to 50%), "moderate exertion" (from 50 to 70%), and "heavy exertion" (from 70 to 100%). The first three exercises (sitting, writing, and stepping) corresponded to the level of daily activity, while the latter two exercises of carrying a school chair and running corresponded to light exertion and moderate exertion, respectively. With the increase in exercise intensity, the mean values of MV, PIF, $\bar{V}_T$, and F also gradually increased from 8.0 to 21.4 L min⁻¹, from 27.1 to 64.6 L min⁻¹, from 0.38 to 0.53 L, and from 21.5 to 40.4 cycles min⁻¹, respectively. The mean values of $\bar{T}_{tot}$ and $\bar{T}_I$ decreased slightly and the ratio of the mean inspiratory time to the mean breathing cycle time ($\bar{T}_I/\bar{T}_{tot}$) increased from 0.41 to 0.47, indicating that the breathing pattern changes according to the intensity of physical activities. Pate et al. (1955) reported that a more than moderate exertion level is usually set for the purpose of the development of physical strength in a gym class, and another study of the heart rates of children in school (Takahashi, 1990) revealed that their exercise intensities seldom exceeded the level of light exertion except during a gym class. Therefore, any test protocol should take measurements up to the level of light exertion, as this the condition under which children are expected to use respirator in school. The test exercises in this study fell within this range, except for running, which exceeded the range slightly.

Table III. Summary of Breathing Data and Estimated Exercise Intensity at Each Test Exercise

Test exercise	%HRR (%)	MV (L min ⁻¹)	PIF (L min ⁻¹)	F (cycles min ⁻¹)	$\bar{V}_T$ (L)	$\bar{T}_{tot}$ (sec)	$\bar{T}_I$ (sec)	$\bar{T}_I/\bar{T}_{tot}$ (-)
Sedentary	7.0	8.0	27.1	21.5	0.38	2.8	1.1	0.41
	4.3	1.3	3.7	3.6	0.05	0.4	0.1	0.02
Writing on Blackboard	17.0	9.6	33.2	25.0	0.39	2.4	1.0	0.42
	7.5	1.9	4.9	4.9	0.07	0.5	0.1	0.03
Stepping	28.0	13.3	42.1	29.6	0.45	2.0	0.9	0.44
	7.6	2.4	7.7	4.4	0.08	0.3	0.1	0.02
Carrying a school chair	41.0	16.9	53.2	34.5	0.50	1.7	0.8	0.46
	10.1	2.6	9.0	5.9	0.08	0.3	0.1	0.02
Running	54.0	21.4	64.6	40.4	0.53	1.5	0.7	0.47
	12.7	5.7	16.9	7.5	0.11	0.3	0.1	0.02

A Proposal for Test Flow Rate of Respirator for Children

The level of physical activity of children wearing respirators in elementary school is up to 50%, which corresponds to a light exertion level. Therefore, in order to clarify an appropriate test flow rate to evaluate the performance of respirator for school children, we focused on the breathing data at an estimated exercise intensity of 50%. Peak inspiratory flow rates represent the instantaneous maximum airflow, which

may temporarily exceed practical requirements (Carette et al., 2006); these are taken into consideration in the Japanese test flow rate of 85 L min⁻¹.

Therefore, the mean $\overline{PIF}$ values for the subjects were plotted against the mean $\overline{\%HRR}$ for each test activity in (Figure 4). The error bars represent double the standard error for each data point. As seen in the figure, the plots of peak inspiratory flow rate were linearly related to increasing exercise intensity. When the peak inhalation flow rate at 50% of exercise intensity was calculated using linear regression, a flow rate of 60.6 L min⁻¹ was obtained. The ratio of this value to 85 L min⁻¹, which is the existing test flow rate of the respirator, is approximately 0.7.

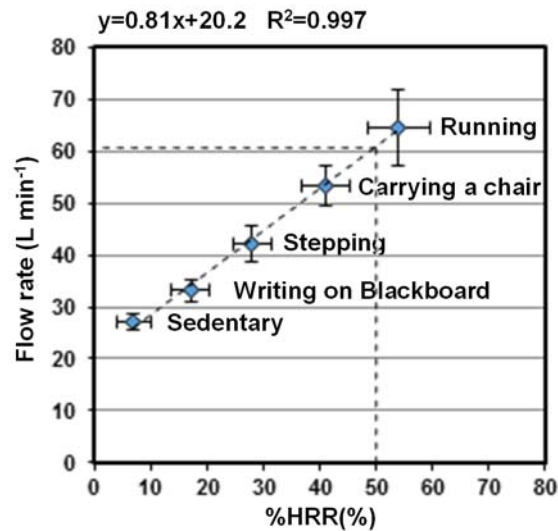


Figure 4. Average ($\pm 2SE$) $\overline{PIF}$ with increased Estimated exercise intensity for the child subjects.

Breathing volumes vary among different physiques, due to the differences in oxygen consumption. The ISO technical specifications (International Standard Organization, 2007), which describes the relationship between metabolic work rate and respiratory flow rate, state that the inhalation minute volume (MV) and peak inspiratory flow rate (PIF) are linearly related to the body surface area.

The ratio of the average body surface area of the child subjects to that of the male subject in the ISO technical specifications is about 0.6, which is close to the abovementioned ratio. This suggests that a flow rate of 60 L min⁻¹ is a reasonable test flow rate for evaluating the performance of dust respirator in children. Moreover, a previous study suggested that particle penetration at a constant flow equivalent to the mean inspiratory flow rate ($\overline{V_T/T_i}$) of the sinusoidal cyclic flow can be used as a good indicator for the performance under the conditions of sinusoidal cyclic flow (Richardson et al, 2006). Further research may be required to explore whether mean inspiratory flow rates can accurately represent actual breathing patterns, which are more complex than a sinusoidal wave form.

Study Limitations

In this study, the breathing recording of children was carried out under simulated usage conditions in elementary schools. Therefore, some differences could occur if the tests were conducted in real school life. This is known as the Hawthorne effect (Roethlisberger et al., 1939), which states that the presence of investigators affects the behavior of workers (Clayton et al., 2012). Similarly, the presence of guardians and investigators during the test period may have caused behavioral and psychological changes in the subjects, which might have affected the results. Moreover, because the pressure drop with wearing the breathing recording masks while children breathing may cause larger respiratory volumes than that without wearing masks. Consequently, the recorded breathing flow may be overestimated using this method. Furthermore, because of difficulty of stable measurement, resting and maximum heart rates for children were referred to literature values for calculation of the exercise intensities. This may cause week exercise intensities for children's physical activities. Although the suggested test flow rate for children's respirator was derived based on the existing test conditions for respirators, an approach that takes the physiological differences between children and adults into account may be needed to create a better protocol.

CONCLUSIONS

We measured the breathing parameters of elementary school children from the first to sixth grades in order to obtain basic information on a suitable test flow rate for evaluating dust respirator for children. By using two types of breathing recording respirator with different facepieces, a good fit, which is key to measurement accuracy, was obtained for all subjects. The mean peak inhalation flow rate of the subjects was linearly related to the mean estimated exercise intensity. Further, the peak inspiratory flow rate at light exertion derived from the regression line was 60.6 L min^{-1} , which corresponds to about 0.7 times the test flow rate of 85 L min^{-1} in the existing standards. The ratio of the body surface area between the child subjects and adult male as defined by the ISO standards was close to this value. Therefore, a test flow rate of 60 L min^{-1} may be appropriate for assessing the performance of respirator for children.

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