Breathing Pattern and Subjective Responses to Small Inspiratory Resistance during Submaximal Exercise

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Breathing patterns and subjective responses to small resistances were investigated in seven subjects during moderate exercise. Inspiratory resistances of 0.15 (R1), 0.25 (R2) and 0.30 (R3) $\text{kPa} \cdot \text{l}^{-1} \cdot \text{s}$ were tested against control of 0.06 $\text{kPa} \cdot \text{l}^{-1} \cdot \text{s}$ with no added resistance. Subjective responses to small inspiratory resistances were evaluated through whole experiments including periods before and after exercise, herein called SNS. Average SNS significantly increased above the R2 condition. Above the R2 condition, significant changes in the breathing components of volume, flow and timing were also observed during exercise. SNS grew as a power function of peak inspiratory pressure (P_{imax}) measured during exercise within such small range of stimulation less than the R3 condition and individual differences in the relationship between SNS and P_{imax} were observed. All subjects felt at least some discomfort below the resistance of R3 and two subjects felt it below around R1 condition. It was suggested that breathing pattern was selected to limit peak pressure at the R3 condition by further increasing inspiratory work for a breath and this tendency was reinforced in load-sensitive subjects with longer inspiratory time and lower peak flow rate. We concluded that breathing patterns depend mainly on peak work, especially in load-sensitive individuals, which is likely to be one of the primary determinants of a worker's tolerance to respirators.

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In Japan, we can find very few studies on the physiological or psychological aspects involved in the use of respiratory protective devices. While we can find much literature on this matter in Europe and America, many reports on the loaded effects have been demonstrated only with high resistances (Flook and Kelman, 1973; ImHof et al., 1986; Lerman et al., 1983), so that the effect of such small resistances as dust respirators were not paid much attention. Japanese are obviously different from Caucasians with respect to physique, absolute maximal oxygen intake and lung size (Yasukouchi, 1986a,b), which might affect breathing pattern (Cerny, 1987) and subjective responses to breathing

load. Therefore, it is important to do experiments using Japanese subjects and to investigate breathing pattern and subjective responses to the small added inspiratory resistances, which in turn might lead to reconsideration of an acceptable level of inspiratory resistance for Japanese workers.

It has been suggested that psychological factors affect breathing pattern (Hudgel and Kinsman, 1983; Shimozaki et al., 1988), and load sensitivity differed considerably even among normal persons (Killian et al., 1981). When existence of Japanese workers who are sensitive even to a small breathing burden is taken into consideration (Homma et al., 1977), we should try to examine individual differ-

ences in subjective responses to breathing load and the characteristics of the sensitive persons, because the resultant findings would provide helpful suggestions for screening such individuals out of jobs requiring respirators.

In this study, we investigated the effects of small inspiratory resistance on breathing pattern and subjective sensation and examined individual differences in the relationships between breathing pattern and load sensation. The characteristic breathing patterns in load-sensitive subjects were also discussed.

MATERIALS AND METHOD

Procedures. Seven male volunteer subjects, aged 23-38 years, participated in this study. One of the subjects had a smoking habit of less than 20 cigarettes a day; the others were nonsmokers. A short spirometry testing was performed to assure normality of the subjects. All were normal and had no history of respiratory disease.

Three different inspiratory resistances of 0.15 (R1), 0.25 (R2) and 0.30 (R3) $\text{kPa}\cdot\text{l}^{-1}\cdot\text{s}$ were employed in this study. Control resistance was 0.06 (C) $\text{kPa}\cdot\text{l}^{-1}\cdot\text{s}$, which was measured through the inspiratory limb of a half facepiece mask to which an anemometer was attached. The subjects performed exercise at a load of 120 W for seven minutes on an electronically-braked cycle ergometer (Isopower Ergometer, Takei, Japan). Although the work load was automatically kept constant independent of the cycling speed, the subjects were encouraged to pedal at around sixty rpm. Rest periods were taken before and after exercise for five and eight minutes, respectively. Each subject was instructed to position a dial at any time throughout the entire experiment according to his sensation of the effect of the resistance on his breathing. The dial was numbered from 1 to 5 and a small panel board, on which the explanation of each number was described, was displayed in front of each subject. The description was as follows; Do you feel difficulty on your

breathing? 1. No, 2. Light, 3. Moderate, 4. Somewhat Heavy, 5. Heavy.

On the first day, each subject experienced wearing simulated respirator and feeling resistance, then exercised on a cycle ergometer in the same manner of the experiment to exclude his anxiety and to establish his psychological scale of breathing difficulty for the dial operation.

Equipment and measurements: A half facepiece mask was employed in this study. This mask was the traditional one used for collecting expired gas to Douglas bag. A hot-wire-anemometer (RF-H, Minato Medical Science, Japan) was placed on the inspiratory and expiratory limbs of the mask to measure respective flow rates, which were calibrated by constant air flow to the anemometer connected to a spirogram. A differential pressure transducer (MP-45, Validyne, USA), calibrated by water manometer, was employed to measure oral pressure. Expired gas was led to an oxygen and carbon dioxide analyzer (Expired gas monitor, Nihon Denki Sanei, Japan) calibrated by standard gases. An inspiratory resistor consisted of a small cylindrical case and stainless steel mesh # 325, which was put into the inlet portion of the anemometer connected to the inspiratory limb of the mask. Steel mesh was not used in the control condition of resistance.

All electrical signals of flow rate, pressure, gas fractions and sensation indicated by the dial were recorded through a data recorder (PCM data recording system, NF Electronic Instrument, Japan) and then transferred to a personal computer (PC-9801VX, NEC, Japan) at a sampling rate of 143.9 times per second.

Calculations: Breathing pattern was analyzed by the personal computer (Yasukouchi and Serita, 1986) and was graphically viewed on a CRT display to assure general validity. The variables calculated are listed in Table 1. All parameters, except minute inspiratory volume (V_i) and sensation (SNS), were determined from breath by breath analysis and

Table 1 Components of breathing pattern

Respiratory flow and volume	
Minute inspiratory volume	($\dot{V}_I$)
Tidal volume	(V_I)
Peak inspiratory flow rate	(PIF)
Mean inspiratory flow rate	(MIF; V_I/t_i)
Peak expiratory flow rate	(PEF)
Respiratory timing	
Inspiratory time	(t_i)
Expiratory time	(t_e)
Total time	(t_t)
Inspiratory: total time ratio	(t_i/t_t)
Respiratory frequency	(R_f)
External respiratory work	
Peak inspiratory pressure	($P_{I\max}$)
Peak expiratory pressure	($P_{E\max}$)
Inspiratory work rate	(WR_i)
Expiratory work rate	(WR_e)
Load sensation	
Difficulty in breathing	(SNS)

averaged for all complete breaths during each one minute throughout the experiment. V_I was determined by integrating inspiratory flow rate for every one minute. Inspiratory work rate (WR_i) and expiratory work rate (WR_e) were calculated by the product of volume and pressure obtained in each sampling interval (about 7 msec) and integrating the product for one inspiration and expiration, respectively, and then converted to the unit of W. All

breathing components were averaged during the last two minutes of each period of rest (before exercise) and exercise in steady state. SNS was determined by the area under a score-time plot obtained from subject's dial operation during the entire period of the experiment. The calculated SNS was assumed to be one of the indices expressing the degree of sensation of breathing difficulty.

RESULTS

Table 2 indicates means and standard deviations of components for breathing pattern at rest and during exercise. Data described show measured values in control and relative values in resistance loaded conditions. In the resting state, V_I , PIF and MIF (V_I/t_i) tended to decrease and t_i and duty cycle (t_i/t_t) tended to increase with resistance. However, all these components of volume, flow and timing at the resistance loaded conditions showed no significant difference compared with control values. In the exercise condition, we could find a significant decrease in V_I and MIF at the load of R3 and in PIF at the loads of R2 and R3. The t_i was prolonged significantly at R2, but did not reach a significant level at R3 due to larger variation of t_i . Duty cycle was significantly increased at R2 and R3. External work for inspiration, such as $P_{I\max}$ and WR_i , indicat-

Fig. 1 Relationship between maximal inspiratory pressure ($P_{I\max}$) and resistance during exercise **Fig. 2** Relationship between inspiratory work rate (WR_i) and resistance during exercise

Table 2 Relative changes in breathing pattern with resistive loading at rest and during exercise

Variables	Rest				Exercise (120 W)			
	C Mean SD	R1 Mean SD (%)	R2 Mean SD (%)	R3 Mean SD (%)	C Mean SD	R1 Mean SD (%)	R2 Mean SD (%)	R3 Mean SD (%)
V_i ($l \cdot \min^{-1}$)	10.48 1.70	104.6 15.6	99.3 7.6	94.1 9.2	40.48 6.46	102.3 9.2	97.3 4.3	94.0* 6.2
V_e (l)	0.68 0.20	104.1 7.4	96.7 9.3	97.9 20.0	1.65 0.26	100.9 4.6	99.7 6.7	112.1 28.7
PIF ($l \cdot \min^{-1}$)	41.0 5.4	110.9 14.7	94.1 14.5	96.3 13.0	125.4 18.4	99.3 14.8	89.7* 9.6	90.1* 11.3
PEF ($l \cdot \min^{-1}$)	28.7 4.5	112.4 28.0	108.6 19.6	103.3 15.0	107.8 19.9	101.7 9.1	99.6 8.2	110.1 23.7
MIF (V_i/t_i) ($l \cdot \min^{-1}$)	29.5 3.9	106.4 13.3	94.4 13.2	93.4 14.9	90.6 11.8	100.4 12.1	93.6 7.8	88.7* 9.6
t_i (sec)	1.459 0.617	98.4 14.9	103.7 17.8	108.7 35.1	1.108 0.295	101.6 11.4	107.9* 7.1	129.7 42.6
t_e (sec)	2.665 1.203	104.0 15.2	94.6 17.0	104.0 29.1	1.445 0.522	97.6 5.8	97.9 5.8	112.6 34.4
t_t (sec)	4.124 1.787	101.6 13.9	97.9 15.7	105.1 28.6	2.554 0.793	98.9 7.5	102.4 3.3	120.3 37.2
t_i/t_t	0.360 0.038	97.4 7.1	106.7 10.1	102.4 14.5	0.440 0.038	102.4 5.3	105.7* 5.8	108.3* 7.1
R_r (cycle $\cdot \min^{-1}$)	16.9 5.3	99.9 12.7	104.4 16.3	100.6 27.7	25.7 7.2	101.3 8.3	97.9 4.0	88.1 19.7
P_{imax} ($kPa \cdot l^{-1} \cdot s$)	0.05 0.00	247.3*** 48.9	296.9*** 43.4	424.1*** 60.7	0.17 0.04	250.6*** 66.1	316.7*** 65.0	448.6*** 107.8
P_{emax} ($kPa \cdot l^{-1} \cdot s$)	0.03 0.00	101.0 26.7	110.1 43.0	97.9 22.8	0.17 0.04	95.0 12.3	94.7 10.8	113.6 37.3
$WR_i (W \cdot 10^{-3})$	21.2 6.5	276.0*** 100.0	314.4*** 70.3	412.3*** 126.6	200.9 63.7	265.6*** 110.8	309.3*** 82.0	403.3*** 139.6
$WR_e (W \cdot 10^{-3})$	6.5 3.3	103.6 31.5	131.1 61.8	129.0 82.6	158.4 71.9	99.6 16.0	98.9 18.1	113.3 49.4

Mean and SD are measured values in control (C) and percentage of control in resistance loaded conditions (R1, R2 and R3). * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$ for comparisons control and each resistive loaded condition. Definitions as in Table 1.

ed an obvious increase at every load in both states of rest and exercise, while expiratory work showed no significant change.

Figure 1 shows the relationship between P_{imax} and resistance in each subject during exercise. P_{imax}

increased linearly with resistance and the correlation coefficient was 0.971. Although WR_i also increased with resistance, the variability was greater compared to that of P_{imax} (Fig. 2).

SNS responses to inspiratory resistive loads are

Table 3 Significance levels of increase in SNS in resistance loaded conditions

	C	R1	R2	R3
C		1.041	2.064	4.860
R1	NS		2.257	3.196
R2	*	*		2.346
R3	***	**	*	

* = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$ for comparisons among control and resistance loaded conditions. The values shown above a diagonal line are t values by a paired t -test.

Fig. 3 Sensitivities to maximal inspiratory pressure (P_{imax}) during exercise in two groups of A and B

shown in Table 3. Significant increase in SNS observed above the R2 load and SNS obtained at R3 significantly increased from any other conditions. SNS grew as a power function of P_{imax} obtained during exercise and individual differences were found by a significant difference in the slopes of Ln SNS on $\text{Ln } P_{\text{imax}}$ (Fig. 3). The slope was 0.111 ($r = 0.464$, $P < 0.05$) in five of seven subjects and 0.496 ($r = 0.868$, $P < 0.01$) in two other subjects, named here groups A and B, respectively. A slope of Ln SNS on P_{imax} was also calculated, which was 0.382 ($r = 0.586$, $P < 0.01$) in Group A and 1.617 ($r = 0.950$, $P < 0.01$) in Group B. When SNS was expressed as a ratio of control value (Fig. 4), the beginning point of the increase was around 0.50 kPa of P_{imax} in Group A, which corresponded to the pressure occur-

Fig. 4 Relative changes in subjective responses to maximal inspiratory pressure (P_{imax}) during exercise in each group

Foot notes: Arbitrary lines are drawn by the eye-fitted

red in the R2 condition, but the magnitude of the increase was small. Two subjects in Group B were considered to be more sensitive to load compared to five other subjects in this study. The beginning point of increase in SNS was already seen just above control or R1 condition.

Figure 5 shows changes of t_i , R_i , PIF and P_{imax} during exercise in each subject. The load-sensitive subjects in Group B tended to have a longer t_i , lower R_i and lower PIF which resulted in showing a lower P_{imax} .

DISCUSSION

It has been widely accepted that load sensation follows Stevens's psychophysical law (Stevens, 1957), or that sensory magnitude grows as a power function of the added loads. The subjective scale employed in this study was not a ratio scale, such as open scale magnitude used by many researchers (Barkers and Tenney, 1970; Harber et al., 1988 a, b; Killian et al., 1981), but an interval scale similar to that of Bentley et al. (1973). Since the psychophysical category scale used by Bentley et al. (1973) had a disadvantage of not reflecting the actual growth of sensation, the subjective responses were

Fig. 5 Changes in breathing components of inspiratory time (t_i), respiratory frequency (R_f), peak inspiratory flow rate (PIF) and maximal inspiratory pressure (P_{imax}) during exercise

Footnotes: Solid and broken lines are Group A and B, respectively

evaluated by the area under the subjective score-time plot during the whole experiment including exercise, herein called SNS. The SNS, as a result, grew as a positively accelerated function of resistive loads in spite of a small range of stimulations (Fig. 3). The method developed for this study might be appropriate to evaluate subjective responses to long-term stimulation of a consistent small load not only during exercise but also during periods before and after exercise, which can simulate actual work-

ing circumstances, rather than an open magnitude estimation which gives short-term stimulation of a widely varying load.

Japanese regulation of an initial inspiratory resistance for dust respirators is below 8 mmH₂O at a flow rate of 40 l·min⁻¹ (0.12 kPa·l⁻¹·s). The initial resistance of recent dust respirators is around 5 mmH₂O·40 l⁻¹ min (0.07 kPa·l⁻¹·s) as a result of much improvement of filtration materials. Most Japanese workers wearing dust respirators change

the filter at a resistance below $0.29 \text{ kPa} \cdot \text{l}^{-1} \cdot \text{s}$ due to a feeling of breathing difficulty (Homma et al., unpublished data). This resistance is relatively small in magnitude compared to those described in most literature. We considered that the effects of smaller resistances should be examined for workers who wear not only chemical cartridge respirators, but also dust respirators. Further, investigations for Japanese responses to small resistive load should be done apart from the abundant data on Caucasians, because physique and physical working capacity in Japanese are, in general, thought to be smaller. Thus, we employed small resistances in this study which represented loads in magnitude occurring in actual working circumstances as to dust respirator use.

Bentley et al. (1973) investigated 158 mine rescue workers during exercise and suggested that 90 percent of a given population should not experience discomfort, if the pressure across the apparatus does not exceed $17 \text{ cmH}_2\text{O}$ under the steady flow condition. The acceptable level for inspiratory resistance was equivalent to $1.37 \text{ J} \cdot \text{l}^{-1}$ of the mean inspiratory work rate according to his coworkers (Love et al., 1977) and they have also suggested that this acceptable level could be applied even to workers over the age of 45 years, including men who suffer from simple pneumoconiosis. Our Japanese subjects started feeling difficulty of breathing from $0.7 \text{ J} \cdot \text{l}^{-1}$ in sensitive subjects and $0.9 \text{ J} \cdot \text{l}^{-1}$ in the other subjects. All subjects felt at least some breathing difficulty under the condition of R3 at which the mean inspiratory work rate did not exceed $1.2 \text{ J} \cdot \text{l}^{-1}$ and the maximal value of peak inspiratory pressure among all subjects was below $7.3 \text{ cmH}_2\text{O}$. Although their results should not be applied for dust or gas masks for longer periods, the level seems to be higher for Japanese workers when compared to our results, even if the differences in subject's occupations and breathing apparatus are taken into consideration. A recent report of Simozaki et al. (1988) indicated that subjective

responses represented by perceived limitation of exercise duration and perceived discomfort did not increase ($P > 0.05$) not only from no load to low inspiratory resistance ($0.20 \text{ kPa} \cdot \text{l}^{-1} \cdot \text{s}$), but also from low to medium load ($0.55 \text{ kPa} \cdot \text{l}^{-1} \cdot \text{s}$). Our average SNS showed no increase from control to R1 condition, but significant increase from control or R1 (0.06 or $0.15 \text{ kPa} \cdot \text{l}^{-1} \cdot \text{s}$) to R2 condition ($0.25 \text{ kPa} \cdot \text{l}^{-1} \cdot \text{s}$). As far as we know, there is no literature regarding an acceptable level of resistance evaluated by Japanese subjective responses to resistive loads. However, Homma et al. (1977) reported that some Japanese workers complained of feeling discomfort at around $7 \text{ mmH}_2\text{O} \cdot 40 \text{ l} \cdot \text{min}$ ($0.10 \text{ kPa} \cdot \text{l}^{-1} \cdot \text{s}$), which is less than the R1 condition in this study. Thus, it is likely that minimum resistance levels of perception of breathing difficulty or keeping exercise without much discomfort in our subjects might be different from those in Caucasian subjects, which might provide one implication of the inadequacy of applying Caucasian data to Japanese workers.

There has been greater information about breathing pattern to inspiratory resistive load, which demonstrated that t_i and duty cycle (t_i/t_e) were increased and PIF and MIF were decreased (Harber et al., 1984, 1988a; Killian et al., 1981). These patterns could be expected adaptation to the resistive loads. In this study, breathing pattern responses to small resistances in the resting state, however, were variable and we could not find any significant differences in breathing components against the control, except P_{imax} and WR_i (Table 2). On the contrary, the expected changes in breathing patterns noted above were found during exercise above the R2 condition at which SNS also significantly increased. However, we were also able to find a great variation in breathing pattern, as suggested by Axen and Haas (1979), which was thought to be reflected by the individual differences in the way of adaptation to small resistances. This difference explained in part a relatively large variability

of WR_i (Fig. 2). In this study, we paid much attention to the individual difference because it was expected that the variability of the breathing patterns were affected by subjective responses to inspiratory loads (Burki 1984; Harber et al. 1988a; Stubbing et al. 1983).

Altose et al. (1981) and Killian et al. (1982) have demonstrated that peak intra-mouth pressure relates closely to sensory magnitude of resistive loads. Our subjects in this study indicated a significant linearity of $\ln SNS/\ln P_{imax}$ even within a small range of resistances, which means that subjective responses throughout the experiment were greatly affected by peak pressure during exercise. However, we found large differences in subjective responses among our subjects. Two subjects (Group B in Fig. 3) who have a significantly steeper slope than five other subjects (Group A in Fig. 3) were considered to be more sensitive individuals. There are very few studies showing a characteristic breathing pattern in load-sensitive persons, while many workers have reported on relations of breathing patterns to respiratory sensations as a group mean (Killian et al., 1980; Stubbing et al., 1981; Zechman and Devenport, 1978). We found differences in breathing pattern between Groups A and B. Harber et al. (1988a) suggested that sensitive individuals tended to choose breathing patterns with relatively low peak inspiratory pressure and short inspiratory time and duty cycle. Our sensitive subjects in Figs. 3 and 4 also indicated a relatively lower P_{imax} ; however, they showed a longer t_i and no characteristic difference in duty cycle, which is contrary to the findings of Harber et al. (1988a).

Characteristics of breathing pattern in our sensitive subjects were also found in the relationship between P_{imax} and WR_i during exercise as shown in Figure 6. The P_{imax} and WR_i in both groups have a linear relationship with a high correlation coefficient of above 0.97 in each condition of resistances. The slopes were statistically constant, but P_{imax} , estimated by regression equations, was significantly

Fig. 6 Relationship between maximal inspiratory pressure and inspiratory work rate during exercise in each group

different among conditions in each group. It is reasonable to consider that WR_i , or breathing patterns would have to be changed at loaded conditions because the peak pressure affecting load sensation increased with increasing load at the same WR_i . Furthermore, the slope in Group B was significantly greater than that in Group A except in the control condition. This means that subjects of Group B should have had to breathe with a greater P_{imax} than others if WR_i had been the same in both groups. Actual P_{imax} in Group B, however, was lower as shown in Fig. 5. Therefore, sensitive subjects in Group B seem to breathe with a smaller work rate, at a given resistive load, caused by longer t_i and lower PIF to limit peak pressure, even if inspiratory work for a breath was enlarged for controlling peak pressure (Fig. 7). Figure 7 shows the relationship between P_{imax} and inspiratory work for a breath during exercise. The P_{imax} increased lineary with increasing inspiratory work from the control to R2

Fig. 7 Relationship between maximal inspiratory pressure and inspiratory work for a breath during exercise in each group

Footnotes: Closed and open circles on the lines are mean values for Group A and B, respectively

condition. However, the increasing rate of P_{imax} deteriorated with greater resistance, which was disclosed by a significantly smaller slope in the R3 condition than other conditions in each group. When regression lines were compared between Groups A and B, P_{imax} in Group B was always significantly smaller than that in Group A at the same inspiratory work for a breath, although the slope was the same in every condition.

Thus, it seems likely that subjects of both groups tend to magnify enlargement of inspiratory work for a breath to suppress the increasing rate of peak pressure with resistances above the R2 load at which SNS significantly increased. The tendency was reinforced in sensitive subjects who chose breathing patterns with longer inspiratory time and lower peak inspiratory flow rate in order to hold peak pressure at a constantly minimum level, which

could be established at the cost of much further enlargement of inspiratory work for a breath. Our findings suggest that breathing pattern depends mainly on peak pleural pressure swings which is likely to determine a worker's tolerance to respirators (Demedt and Authonisen, 1975). The characteristic pattern is supported by the implication of Harber et al. (1984) that breathing pattern is selected to limit peak work rather than minimize average work. Our previous study (Yasukouchi and Serita, 1989) implicated that further prolongation of t_i in the detected responses were attributed to conscious or subconscious aspects of loading responses.

The number of our sensitive subjects was too small in this study. We have therefore completed a further series of experiments in ten different subjects under the same resistance conditions (in preparation for another paper). In that study, five subjects selected from 33 persons were considered to be more sensitive to resistive loads. The subjects exercised with a bicycle ergometer at work loads from 50 to 130 watts and the five more sensitive subjects had a significantly greater SNS in R3 condition than the others. Those sensitive subjects showed significant increase in t_i at every work load and significant decrease in MIF at a load of 130 watts while the other subjects showed no change of t_i and MIF. As a result, tidal volume tended to increase and respiratory frequencies decreased in sensitive subjects. These tendencies were consistent with the results in this study.

Our results during exercise demonstrated that breathing patterns and subjective responses were affected by inspiratory resistances as small as those of dust respirators and breathing patterns were selected to control peak inspiratory work by the increase in an average work to minimize discomfort to such small loads. It was revealed that some subjects started feeling difficulty in breathing from very small resistive loads even when they felt no discomfort at rest before exercise. These subjects showed a characteristic breathing pattern of further

prolongation of inspiratory time and lower peak inspiratory flow rate. Although we should perform more intensive studies encompassing a larger number of Japanese workers as well as sensitive individuals, our findings might provide helpful data for those decisions regarding an acceptable level of resistive load and an individual's fitness for respirator use.

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