# Effects of Industrial Respirators on Respiratory Timing and Psychophysiologic Load Sensitivity

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*Loads imposed by industrial respirators include inspiratory flow resistance and dead space. Eleven normal subjects were studied at five levels of treadmill exercise (from resting to peak) with and without a respirator surrogate load (single air-purifying cartridge plus 300 ml dead space). Analysis of variance with linear contrasts was used to separate interpersonal from respirator effects. The respiratory pattern was significantly affected, prolonging inspiration, decreasing peak inspiratory flow rates, and increasing tidal volume. Sensitivity to respiratory loads was measured by the magnitude estimation method; the respirator load, but not exercise, decreased load sensitivity. Interpersonal differences in load sensitivity were relatively large. This study suggests that tolerance to respiratory loads similar to those of respirators may be significantly affected by respiratory timing and load sensitivity adaptation. Poor tolerance by some workers might be related to abnormal psychophysiologic load sensitivity.*

Respirators, personal protective devices for protection against inhaled toxins, are worn by many American workers. Physicians are involved in medically certifying workers for respirator use [1-5] and must also occasionally consider their use in persons with respiratory disease. For example, the Cotton Dust Regulations[6] state that a physician's opinion about ability to use a respirator may eliminate a worker's job, and the Arsenic Standard refers certain respirator users to a "physician with training in pulmonary medicine."[7] Respirators have been suggested for use in nonoccupational settings for prevention of hypersensitivity pneumonitis[8] and exercise-induced bronchospasm[9] as well as for protection against ozone.[10]

Therefore, an understanding of their effects is needed. In addition to imposing physiologic burdens, they may produce "subjective" discomfort which precludes their use in some persons. Several studies have indicated poor compliance with proper use,[11,12] and Levine[13] demonstrated that intermittent use may be no better than non-use. Additionally, understanding adaptation to respirator use may facilitate understanding of tolerance of other respiratory loads.

Several previous studies[14-24] have shown effects upon peak work tolerance and ventilatory flows. These have led to opposite conclusions about the need for clinical physiologic testing. Raven et al[25] concluded that specific pulmonary function tests (eg, maximum voluntary ventilation) should be done, whereas Hodous et al[26] concluded, "if a worker was performing his duties without problems without a respirator, it is unlikely that a respirator will cause difficulty."

Use of a respirator may be determined by ability to overcome the adverse effects of the respirator on ventilatory mechanics (eg, total resistance and dead space) or by respiratory control effects. To investigate whether dead space and inspiratory flow-resistive loading (similar to that of many respirators) had important effects on variables other than the "mechanical" factors such as flow and pressure, we studied respiratory timing and sensitivity response in a group of volunteers in an exercise laboratory setting. These studies demonstrated significant effects, suggesting that such "nonmechanical" factors may be important determinants of satisfactory adaptation to such loads.

## Methods

Eleven healthy volunteers were studied in a protocol approved by the UCLA Human Subject Protection Com-

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mittee. Six were women; the subjects were between 22 and 39 years of age. After explanation of the study, each signed an Informed Consent Statement and underwent a limited medical interview and examination. Spirometry was performed with a dry rolling seal spirometer (Ohio 822, Houston).

Subjects employed a noseclip and breathed through a mouthpiece with a low-resistance one-way Koegel valve. Pneumotachographs (Fleisch No. 3) on the inspiratory and expiratory limbs and pressure transducers (MP-45, Validyne, Northridge, CA) were used for flow measurement. A tap at the mouthpiece was connected to a pressure tranducer (MP-45, Validyne, Northridge, CA) to measure mouth pressure. Expired air passed through a large low resistance mixing chamber in contact with a water reservoir to allow expired air to reach thermal equilibrium with the ambient temperature prior to passing through the expiratory pneumotachograph. Amplifiers (Hewlett-Packard 7754, 8805C, Waltham, MA) conditioned the signals. A respiratory integrator (Hewlett-Packard 8815) was used as a flow integrator to measure inspiratory volumes. Gas tensions ($N_2$, $O_2$, $CO_2$) were measured with a respiratory mass spectrometer (Perkin-Elmer Model 1100, Pomona, CA). A tap at the distal end of the mixing circuit was used for measuring mixed expired gas tensions. The signals from the expiratory pneumotachograph, cardiotachometer, and gas tension analyzers were digitized (Hewlett-Packard 47310A) and analyzed on-line by a microcomputer (Hewlett-Packard 9825, Corvallis, OR). The program employed has been previously described.[27] The signals from the inspiratory pneumotachograph, mouth pressure transducer, and respiratory work integrator were digitized (Hewlett-Packard 47310A) and recorded on tape for subsequent off-line analysis by another microcomputer (Hewlett-Packard HP85, Corvallis, OR) which was also used for the subsequent statistical analyses. Computer programs were developed specifically for this study and were validated prior to utilization. Mixed expired gas tensions were read from the calibrated digital display of the mass spectrometer.

A respirator load was simulated by imposition of an inspiratory flow resistance and dead space load. The resistance consisted of a single acid-mist respirator cartridge (MSA, Pittsburgh). Its flow-pressure characteristics were approximately linear in the flow range of 0.2 to 1.5 L/s, and its resistance was 5 cm of $H_2O$/L/s in this range. A 300-ml cylindrical dead space, chosen to be slightly less than the physical mask volume of a large full-face mask, was placed between the mouthpiece and the valve.

Oxygen consumption and $CO_2$ excretion were determined by the mixed expired method[28]; values were expressed in standard temperature and pressure (STP) terms. Oxygen consumption and carbon dioxide excretion were also measured using a breath-by-breath method[27] during unloaded breathing. Results were similar to those obtained by analysis of mixed expired gas.

The respiratory pattern was characterized by several parameters: inspiratory time ($T_i$), expiratory time ($T_e$), total respiratory cycle time ($T_{tot}$), average inspiratory flow rate (tidal volume/$T_i$, $V_t/T_i$), duty cycle ($T_i$:$T_{tot}$), and peak inspiratory flow rate. An additional parameter described the "squareness" of the inspiratory flow pattern; the "time average" inspiratory flow rate was determined by averaging the inspiratory flow rate for each 20-ms period of each breath. The time for which flow was greater than this average was then determined. Respiratory timing periods were calculated by considering the inspiratory period to be that period in which there is positive inspiratory flow, and the total time ($T_{tot}$) to be the period from the initiation of inspiratory flow of one breath to that of initiation of inspiratory flow for the subsequent breath. $T_e$ was determined by subtraction of $T_i$ from $T_{tot}$; thus an end-inspiratory pause, if any, is included in the $T_e$.

Sensitivity to inspiratory flow-resistive loads (load scaling) was determined by the technique of magnitude estimation. A series of 10 inspiratory flow resistances were presented in random order for two breaths each, separated by several breaths with no added resistance. The resistances were approximately linear and ranged from 1 to 30 cm of $H_2O$/L/s. The individual resistance elements were constructed of fine mesh wire, paper laboratory filters, and gauze held in place by a wide mesh screen. Each resistance element was placed in a 4-inch polyvinyl chloride pipe holder for easy use. During the load scaling procedure, a "Y" device was utilized; one limb of the Y was connected to the inspiratory limb of the breathing circuit, a second limb was connected to a DuBois shutter, and the third limb was used for placement of the resistance elements. With the shutter open, the investigator could change the resistance in the third limb without affecting the respiratory sensation of the subject, since there was minimal resistance to breathing through the second limb. When the resistance was in place, the shutter was activated during the expiratory phase of a breath, and the next inspiration was therefore through the resistance element.

Each load scaling sensitivity determination was based on estimates for 10 resistances. Prior to starting, the highest resistance was presented to the subject to illustrate the method. The subject was then asked to "rate" each of the 10 resistances. The subject wrote his/her estimate on a form and was unable to see his/her previous responses. Each subject's load sensitivity for each "set" was determined by Steven's physchophysical law (perception is proportional to a power of the stimulus).[29] In this case, $P = KR^n$, where P is the perceived resistance, R is the actual added resistance, and n is the exponent describing the load sensitivity. A plot of log(P) *v* log(R) was prepared, and a line was fitted using the least-squares technique; the slope of the line estimated the sensitivity (n). As described below, duplicate sets were performed during rest, and the results were averaged. The linear correlation coefficient (*r*) for the line as well as the slope was recorded.

Each subject participated in the same protocol, which is summarized in Table 1. After explanation of the study, completion of an informed consent statement, limited history and physical examination, and spirometry, the subject was allowed to become accustomed to breathing with the apparatus. The load scaling procedure was then explained, and several sample resistances were added. A series of experimental periods followed. Each period was at least six minutes, duration determined by time necessary to reach stability (manifested by respiratory rate and heart rate stability for at least 60 seconds before data collection). In general, only the rest periods required extension. Although respiratory and heart rate parameters were monitored continuously, measurements for analysis were made in the last two minutes of each period; if load scaling was performed in a period, it was accomplished after measurements were made. Load scaling required between 1 1/2 and four minutes (requiring more time during rest because of a lower respiratory rate). Temperature and humidity were the ambient conditions in the heated and air-conditioned exercise laboratory. Subjects were given free access to water before the study and during the rest period. The "maximal" exercise was performed by increasing the incline of the treadmill to a level which the experimenter estimated would produce exhaustion in the subjects within several minutes; although the angle differed between subjects, it was the same for each subject with and without the respirator load in place. The measurements were begun 30 to 60 seconds after onset of the maximal exercise.

Statistical analyses were performed using parametric methods. Paired *t* tests were used to compare the results in the comparable experimental periods (eg, rest loaded with rest unloaded, maximal loaded with maximal unloaded). Two-way analysis of variance was used to detect overall effects of respirator loading.[30-32] Analyses were performed for each of the physiologic variables to consider the effects of subject and experimental period. The F test was used to determine whether the subject of the experimental period had a statistically significant effect. If the experimental period was a significant factor, then the method of linear contrasts[30-32] was employed to separate the effects of respiratory loading. For clarity in presentation of graphic data, group means for each period are displayed, although the statistical analyses did not directly compare group means. A two-tailed *P* less than .05 is considered statistically significant for purposes of this report.

## Results

All subjects had normal forced expiratory volumes in 1 second ($FEV_1 > 80\%$ of predicted) and normal forced vital capacities ($FVC > 80\%$ of predicted).[33] No cardiopulmonary abnormalities were noted on examination. Data from one subject who was unable to complete the maximal exercise periods are not included in analyses including these periods.

Respiratory timing results are shown in Table 2 as group mean ± SD. In addition, the analysis of variance results are shown, including F for period effect, F for "person" effect, and mean adjusted difference due to respirator load (as determined by linear contrasts). Respiratory rate was increased by exercise, but showed no significant effect of the respirator load. However, there were significant changes in the distribution of time within the total respiratory cycle ($T_{tot}$). The inspiratory time ($T_I$) was significantly prolonged by the respiratory load. The duty cycle ($T_I$:$T_{tot}$) was similarly affected. However, unlike the inspiratory time, the duty cycle did not tend to be less affected at higher work rates in comparison to lower work rates. Figure 1 illustrates the $T_I$ and $T_I$:$T_{tot}$ results; the lines of loaded and unloaded periods are approximately parallel for $T_I$:$T_{tot}$, suggesting that the absolute magnitude of the effect is independent of the work level. Time with greater than average inspiratory flow, a measure of "squaring" of the inspiratory pattern, was significantly increased by the dead space and inspiratory resistance load. Expiratory time showed a minor, nonstatistically significant tendency to be decreased by the load. The mean inspiratory flow rate ($V_t$:$T_I$) showed no statistically significant changes due to the respirator load; however, a tendency to be decreased at the two highest work loads may be discerned in Table 2.

**TABLE 1**
Experimental Periods

| | Load | Speed | Grade | Load Scaling |
|---|---|---|---|---|
| 1. Rest | – | 0 | 0 | +, + |
| 2. Low | – | 2 | 0 | + |
| 3. Moderate | – | 3 | 0 | |
| 4. High | – | 3 | 10 | + |
| 5. Maximal | – | 3.8 | Varied* | |
| Rest period | | | | |
| 6. Rest† | + | 0 | 0 | +, + |
| 7. Low | + | 2 | 0 | + |
| 8. Moderate | + | 3 | 0 | |
| 9. High | + | 3 | 10 | + |
| 10. Maximal | + | 3.8 | Varied | |

* Variable between subjects; same for periods 5 and 10 for each subject.

† Periods 6 to 10 were performed before periods 1 to 5 in some subjects; assignment was random.

Pressures, volumes, flows, and oxygen consumption are reported in Table 3, employing a format similar to that of Table 2. Peak and average mouth pressures were, of course, increased by the load (although the difference did not reach statistical significance at the highest exercise levels due to the variability). Peak inspiratory flow rate was depressed by the respirator loading, and the magnitude of the effect was greatest at the higher exercise levels. Tidal volume showed a modest, but statistically significant increase due to the load, but the observed increase of the minute volume was not statistically significant. Oxygen consumption and heart rate were not significantly affected by the respiratory load.

The results of the magnitude estimation of added resistive loads (load scaling) are shown in Table 4. The mean sensitivity exponent was 0.753 without the load at rest and 0.655 in the loaded state at rest. Figure 2, illustrating the effect of the experimental periods on load sensitivity, shows a consistent pattern: exercise had no significant effect, while the dead space resistance (respirator) load decreased sensitivity at each of the three exertion levels studied (although only the overall effect reached statistical significance). The correlation coefficient relating ln(P) and ln(R) for each subject averaged .90 at rest without the added load, and the overall average was .83.

**TABLE 2**
Respiratory Timing Results*

| | | Exercise Level | | | | | Period F | Person F | Load Effect |
|---|---|---|---|---|---|---|---|---|---|
| | | Rest | Low | Mod | High | Max | | | |
| Rate ($min^{-1}$) | NL | 14.60 ± 5.01 | 19.30 ± 4.9 | 21.40 ± 5.3 | 30.1 ± 10.0 | 31.90 ± 11.1 | 19.0† | 15.3† | NS‡ |
| | L | 13.50 ± 4.02 | 17.70 ± 4.7 | 20.80 ± 5.5 | 28.2 ± 9.2 | 32.90 ± 9.3 | | | |
| Inspiratory time (s) | NL | 1.54 ± 0.62 | 1.31 ± 0.45 | 1.28 ± 0.41 | 1.11 ± 0.41 | 1.12 ± 0.43 | 5.9† | 15.5† | † |
| | L | 1.83 ± 0.49 | 1.70 ± 0.62 | 1.53 ± 0.43 | 1.32 ± 0.48 | 1.20 ± 0.39 | | | |
| Duty cycle (× 100%) | NL | 33.70 ± 5.9 | 39.28 ± 4.7 | 42.75 ± 4.4 | 50.07 ± 5.0 | 52.83 ± 5.2 | 43.3† | 12.0† | † |
| | L | 38.75 ± 5.3 | 46.41 ± 4.0 | 49.98 ± 5.6 | 56.06 ± 6.9 | 60.71 ± 6.4 | | | |
| Mean inspiratory flow (L/s) | NL | 0.44 ± 0.2 | 0.70 ± 0.17 | 0.86 ± 0.25 | 1.38 ± 0.51 | 1.69 ± 0.68 | 29.2† | 11.5§ | NS |
| | L | 0.49 ± 0.14 | 0.69 ± 0.17 | 0.85 ± 0.21 | 1.23 ± 0.34 | 1.52 ± 0.40 | | | |
| Expiratory time (s) | NL | 3.07 ± 1.13 | 2.05 ± 0.72 | 1.77 ± 0.76 | 1.16 ± 0.56 | 1.05 ± 0.58 | 22.9† | 16.4† | NS |
| | L | 2.97 ± 0.94 | 1.96 ± 0.63 | 1.58 ± 0.61 | 1.09 ± 0.59 | 0.81 ± 0.47 | | | |

* Group means ± SD for each exercise level are shown for periods with no load (NL) and with the respirator load (L). ANOVA F values are shown for Period Effect and Person Effect. The last column indicates statistical significance of the effect of the load, as determined by linear contrasts.
† $P < .01$.
‡ NS = not significant at $P > .05$.
§ $P < .05$.

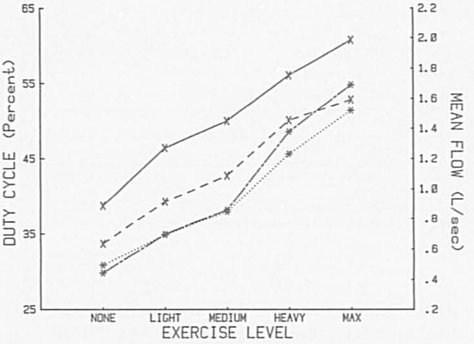

**Fig. 1.** Respiratory timing. Duty cycle (inspiratory to total time ratio) for periods with no load (dashed lines) and respirator load (solid lines) and mean inspiratory flow rate without (dash-dot line) and with (dotted line) the respiratory load are shown for each exercise level. Points represent group averages for each period.

## Discussion

### Physiologic Adaptation

In this study, we examined the effects of respiratory loads similar to those imposed by many industrial respirators and certain lung diseases (inspiratory flow resistance and dead space). Three groups of variables were studied—"mechanical" (pressures, flows, volumes, $O_2$ consumption, heart rate), respiratory pattern, and psychophysical (load scaling sensitivity). The mechanical effects have been emphasized in most previous studies of the physiologic effects of respirators.[2-5,14-25] The study was performed using several levels of submaximal exercise as well as peak exercise.

Exercise produced the expected results—increases in flow rates and volumes, shortening of both inspiratory and expiratory portions of the respiratory cycle, increased metabolic activity, and increased heart rate.

Inspiratory loading per se did not significantly affect the metabolic and cardiac parameters. This is consistent with previous studies.[14,19,21,23,26,34] Change in heart rate by the use of a respirator may indicate an abnormal response due to anxiety or physiologic factors[4] or may be caused by carrying the weight of a self-contained breathing apparatus respirator.[34,35]

Relatively small effects upon the mechanical factors were noted. Tidal volume increased slightly, most likely due to the dead space loading[37-39] and possibly due to the inspiratory resistance per se.[40] The dead space and resistance components of the respirator load have offsetting effects on minute ventilation. Inspiratory resistance per se decreases minute ventilation.[16,32,36,41] Although small increases in arterial and end-tidal $CO_2$ tensions occurred with relatively low resistances,[15,16] Deno et al[22] showed significant hypercapnea due to large resistances.

The pattern of breathing was affected. Peak inspiratory flow rates were decreased, and inspiration was prolonged, both absolutely ($T_I$) and in relative terms (duty cycle). The inspiratory pattern tends to be "square," as suggested by the increase in inspiratory time during which flow is greater than average. Since minute ventilation is the product of the mean flow rate and the duty cycle,[42] increases in the latter may offset decreases in the former.

Subjects use a mode of breathing during loading at submaximal exercise which has not reached maximal possible change. Although the respiratory load tended to increase the inspiratory time, with high exercise and the respirator load in place, the inspiratory time was actually shorter than at low levels of exercise without any respirator load.

These effects on respiratory timing noted in this study are generally similar to those reported in previous

### TABLE 3

Mechanical and Metabolic Variables*

| | | Exercise Level | | | | | Period F | Person F | Load Effect |
|---|---|---|---|---|---|---|---|---|---|
| | | Rest | Low | Moderate | High | Maximal | | | |
| Peak mouth pressure (cm $H_2O$) | NL | 1.37 ± 0.43 | 1.61 ± 0.44 | 2.19 ± 0.29 | 2.77 ± 0.44 | 3.82 ± 1.17 | 45.9† | 3.6‡ | † |
| | L | 4.26 ± 1.22 | 6.00 ± 1.00† | 8.18 ± 1.52† | 12.69 ± 4.00 | 15.75 ± 5.16 | | | |
| Average mouth pressure (cm $H_2O$) | NL | 0.64 ± 0.21 | 0.82 ± 0.32 | 1.12 ± 0.25 | 1.52 ± 0.29 | 2.15 ± 0.78 | 46.1† | 4.4† | † |
| | L | 2.85 ± 0.75‡ | 4.02 ± 0.72† | 5.12 ± 1.16‡ | 8.11 ± 2.59‡ | 10.44 ± 3.76 | | | |
| Peak inspiratory flow (L/s) | NL | 0.68 ± 0.32 | 1.14 ± 0.24 | 1.48 ± 0.28 | 2.25 ± 0.72 | 2.75 ± 0.78 | 41.4† | 7.8† | † |
| | L | 0.71 ± 0.17 | 1.04 ± 0.16 | 1.29 ± 0.21 | 1.87 ± 0.44 | 2.35 ± 0.49 | | | |
| Tidal volume (L) | NL | 0.63 ± 0.31 | 0.86 ± 0.27 | 1.12 ± 0.64 | 1.52 ± 0.84 | 1.72 ± 0.72 | 19.5† | 38.3† | ‡ |
| | L | 0.89 ± 0.34 | 1.17 ± 0.44 | 1.29 ± 0.44 | 1.63 ± 0.75 | 1.82 ± 0.74 | | | |
| Minute ventilation (inspiratory, L/min) | NL | 8.78 ± 2.81 | 16.23 ± 4.19 | 22.28 ± 6.71 | 42.93 ± 15.85 | 55.41 ± 18.34 | 3.9† | NS§ | NS |
| | L | 11.85 ± 2.56 | 21.80 ± 4.87 | 26.37 ± 5.91 | 38.40 ± 11.42 | 53.18 ± 13.70 | | | |
| Oxygen consumption (L/min, STP) | NL | 0.25 ± 0.12 | 0.71 ± 0.17 | 0.80 ± 0.29 | 1.50 ± 0.46 | 1.82 ± 0.56 | 32.5† | 7.2† | NS |
| | L | 0.30 ± 0.07 | 0.63 ± 1.19 | 0.84 ± 0.22 | 1.49 ± 0.48 | 1.83 ± 0.48 | | | |
| Heart rate ($min^{-1}$) | NL | 89.6 ± 11.4 | 100.5 ± 19.5 | 118.6 ± 17.1 | 142.6 ± 26.3 | 164.3 ± 27.0 | 19.4† | 4.2 | NS |
| | L | 93.4 ± 14.1 | 97.4 ± 33.4 | 115.0 ± 16.4 | 149.6 ± 26.6 | 158.6 ± 21.4 | | | |

* Data are presented as in Table 2. NL = no load; L = load. Footnotes accompanying data in the Rest through Maximal exercise level columns indicate statistical significance of differences due to use of the load at that exercise level (as determined by paired *t* tests).

† $P < .01$.

‡ $P < .05$.

§ NS = not significant at $P > .05$.

### TABLE 4

Load Scaling Sensitivity*

| | | Exercise Level | | | | | Period F | Person F | Load Effect |
|---|---|---|---|---|---|---|---|---|---|
| | | Rest | Low | Moderate | High | Maximal | | | |
| Sensitivity (exponent) | NL | 0.753 ± 0.31 | 0.857 ± 0.41 | – | 0.744 ± 0.44 | – | 2.5† | 7.0‡ | ‡ |
| | L | 0.655 ± 0.35 | 0.651 ± 0.32 | – | 0.515 ± 0.16 | – | | | |

* Data were determined by magnitude estimation as defined in text with no load (NL) and load (L) at several exercise levels.

† $P < .05$.

‡ $P < .01$.

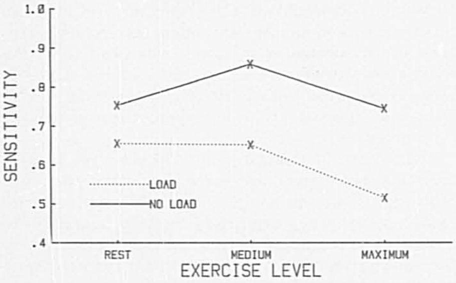

**Fig. 2.** Load sensitivity. Load sensitivity (as defined in text) is shown for several exercise levels without (solid line) and with (dotted line) the respiratory load in place. Group averages for each period are shown.

studies. Inspiratory resistance prolongs inspiration,[5,19,23,36,43] although dead space itself does not affect timing.[34,35,38,39] Hence, the observed effects are those of resistive component. Expiratory phase shortening, which was not conclusively demonstrated in this study, has been found by some workers[24,44–47] but not by others.[19,23,24] Considerable "reserve" in adaptation was manifest since progressive decreases in the expiratory time occurred as the level of exercise increased. It is therefore unlikely that at low to moderate submaximal exercise, expiratory time compression is the factor which critically determines which worker can effectively utilize a respirator.

The ventilatory pattern is also affected by disease states, as recently summarized by Tobin et al.[48] Asthma, chronic obstructive pulmonary disease, and interstitial lung disease all affect inspiratory timing and may therefore affect respiratory control effects in addition to their effects on overcoming the ventilatory mechanical effects of respirators.

These studies employed a dead space with a volume chosen to be comparable to the water displacement volume of many full-face mask respirators. However, the "effective" dead space of both actual respirators and of our cylindrical surrogate is probably less than this value due to air streaming.[33,37,39,49] External dead space increases tidal volume,[38,39] as does added inspiratory flow resistance. Sackner et al[39] suggest that the increases in tidal volume are greater in magnitude than the actual added effective dead space. Since studies showed no significant effect of dead space on inspiratory time or total respiratory cycle time, the increases observed in this study are likely to be due to an effect of the resistance rather than the dead space.

Several workers have investigated $CO_2$ loading during exercise with respirators,[47,50] but these studies may not be directly applicable to analysis of effects of dead space during exercise.[47,51]

### Psychophysiologic Adaptation

This study shows that psychophysiologic sensitivity to inspiratory flow resistance is affected by the respirator type loads. This study employed magnitude estimation, a quantitative method of assessing sensitivity to resistive loads[52–54] based upon Steven's general psychophysical law,[29] which states that the perception is related to a power function of the stimulus. This method may be more "objective" than simple subjective ratings of discomfort[55] because it is based upon the relationship between increments in sensation and increments in stimulus rather than the absolute level of the sensation reported. Subjects appear to adapt to the respirator-type load by decreasing their sensation of loads. With the load in place, subjects were less affected by any additional resistance which was added. Stubbing et al[56] showed that the ability to detect added resistance varied in proportion to the background resistance. There have been limited previous studies of effects of loading on the magnitude of perception (rather than detection) of added loads. Gottfried et al[57] and Revelette et al[58] found small decreases in load sensitivity induced by inspiratory-resistive loading at rest. Burdon et al[59] however, found that the sensitivity did not change;[59] however, in this experiment, the background load was only briefly present, and the subject's breathing patterns were controlled by the investigators. Numerous other factors can affect respiratory sensation.[60–63]

Increased ventilation induced by $CO_2$ breathing did not affect sensitivity,[64] suggesting that the effect noted in the current study is due to the resistance rather than the dead space component.

Although the empiric data and theoretic analysis suggest an effect of respiratory loads on load sensitivity, much of the overall variance in sensitivities is explained by interpersonal factors rather than by the experimental period. Killian et al[53] also noted large interpersonal differences in sensitivity which are not explained by disease states such as chronic obstructive pulmonary disease which may decrease sensitivity.[65,66] Hudgel et al[67] reported that "behavioral style" had influenced the ability to detect minimal resistances.

Pressure swings appear to limit tolerance of resistive loads.[18,36,41,55] Pressure or the pressure-flow relationship[54] rather than resistance itself may be the "signal" involved in perception of load, and a person's load sensitivity may determine his/her particular tolerable pressure swing. The wide interpersonal range of tolerable pressure swings[36] and the interpersonal variability in load sensitivity may partially explain differences in respirator tolerance in apparently "normal" persons. This study has demonstrated major effects of the inspiratory flow-resistive and dead space loads of respirators on respiratory timing and load sensitivity. It is quite possible that these adaptations are the true determinants of suitability for respirator use. Those who do not adopt an appropriate respiratory pattern or who fail to decrease load sensitivity may tolerate respirators poorly. In addition, the wide interpersonal variability in load sensitivity may explain why some apparently "normal" persons tolerate respirators poorly. Thus, the psychophysiologic sensitivity, rather than muscular ability to overcome resistance, may determine whether a worker is comfortable employing a respirator. Further studies of psychophysical factors, particularly if subjective responses are also recorded, may help explain tolerance of and compliance with respirator use.

Understanding of the physiologic and psychophysical effects of respirators is critical for the development of improved respirators and/or medical evaluative procedures to match the right worker with the right respirator. Although the study demonstrated the presence of certain effects, their significance as determinants of respirator tolerance in normal and pulmonary-impaired persons needs to be verified in future studies. "Respirator wearer's strain"[69] is clearly a multifaceted problem.

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