

and fine wire mesh within 3-inch (7.5 cm) diameter tubing to produce desired resistances which were approximately linear in the 0 to 2 L/s flow range.

Physiologic measurements were made by data collection with an analog-digital converter (Hewlett Packard 47310A, Corvallis, Ore) and microcomputer (Hewlett Packard 9816) at a rate of 50 Hz. Pressure was measured from a mouthpiece tap with a pressure transducer (Validyne, Northridge, Calif). Flow was measured with a Fleisch no. 3 pneumotachograph (Hewlett-Packard) and pressure transducer (MP-5, Validyne). Data were analyzed using programs developed for this project.

Inspired minute ventilation (V_i) and tidal volume (V_t) were calculated and expressed in body temperature, pressure, saturated (BTPS) conditions. Respiratory timing was characterized by inspiratory time (T_i), expiratory time (T_e), total respiratory cycle Time (T_{tot}), and respiratory rate (RR). The duty cycle (DC) is the fraction of the respiratory cycle during which inspiratory muscles are active ($T_i:T_{tot}$). The added ventilatory inspiratory work due to added loads (to overcome the external inspiratory resistance) was calculated as the pressure-volume integral (W_{tot} , in $\text{cm H}_2\text{O} \times \text{liters}$). Peak inspiratory work rate is expressed as the product of peak inspiratory flow rate and maximal inspiratory pressure. The force of the respiratory muscles was expressed as the peak inspiratory pressure (P_{max-i}), the average inspiratory pressure (P_{avg}) and as the pressure-time integral ($P \times T$). Maximal and average inspiratory flow rates were also determined (F_{max-i} and F_{avg}). Pressures are expressed in $\text{cm H}_2\text{O}$, volumes in liters BTPS, flows in liters/s BTPS, times in seconds, and gas tension in torr.

During the experimental periods in which actual respirators were used, measurements with a mouthpiece were not possible. However, respiratory timing was determined with a respiratory inductive plethysmograph (Respirace, Ambulatory Monitoring, Ardsleigh, NY).

Psychophysical sensitivity to added inspiratory resistive loads was determined as the load scaling sensitivity (LSS) using a modification of the magnitude scaling method.¹⁵ Subjects breathed normally while seated at rest. A series of 12 resistances (2 to 25 $\text{cm H}_2\text{O}/\text{liter/s}$) were interposed in the inspiratory limb for two breaths each in random order; several unloaded breaths were interposed between resistances. Subjects wrote a number to describe their sensation for each breath using an open scale. The actual resistance used and the peak pressure generated were recorded. Resistances were constructed by the method described earlier.

LSS was determined by Steven's Law,¹⁶ which states that sensation is proportional to the stimulus raised to a power (n). The power is the LSS. LSS was calculated as the slope of the line relating the logarithm of sensation to logarithm of stimulus. The LSS was calculated using the actual added resistance as the stimulus (LSS-R) and using the peak pressure as the stimulus (LSS-P). LSS determination was performed twice, each time with a set of 12 resistances. Load scaling was performed separately from the respiratory exercise studies; for half the subjects, it preceded the exercise study.

The subjective sensation of tolerance of breathing was measured with two visual analog scales. They were constructed so that the subject could indicate subjective sensation by placing a mark on a vertical line. The vertical position of the mark indicated the magnitude of the effect. Descriptive phrases were printed along the vertical line to provide reference points. Two separate scales were used. The first (Time Limit) asked, "How long could you continue exercising like this?" The second (Discomfort) asked, "How uncomfortable is this?" The scales were designed so that a high mark on scale 1 indicated minimal intolerance, whereas a high mark on scale 2 indicated considerable intolerance. Results were measured as distance (millimeters) from the base of the line. Results for each experimental period were expressed as the difference from the rating in the NL period.

Statistical analyses were performed using BMDP programs for a microcomputer.¹⁷ Analyses were performed using data from all experimental periods (ALL), no load periods (NL), and from the "standard" load periods, which were common to all subjects (DIM). The subjective sensations are described as absolute values (scale 1 and scale 2 for the Time Limit and Discomfort scales, respectively) or as the subject's difference between the rating in the experimental period and the NL period ($\Delta 1$, $\Delta 2$). Simple linear regression analyses of physiologic variables upon the subjective measures (Table 2) and subjective measure upon LSS (Table 3) were performed. In addition, multiple linear regressions of subjective tolerance upon T_i , P_{max-i} , and LSS-P were performed (Table 4). Regression coefficients are considered significant if $P < .05$ and of borderline significance if $.05 < P < 0.10$. Correlation coefficients express the closeness of linear association.

Results

Two visual analog scales were used to describe subjective tolerance. The first (Time Limit), was arranged so that higher scores reflect better tolerance (ability to continue longer). Conversely, for the second scale (Discomfort), higher scales reflect greater discomfort.

The linear relationships between physiologic variables and subjective tolerance are summarized in Table 1. Each of the several measures of the added work of ventilation was linearly related to the subjective response. Measures of average, integrated, and peak work and pressure all appeared related to both the Time Limit and Discomfort measures of tolerance. Because of the high degree of colinearity (correlation) among the several measures, it is not possible to determine which of the several measures is most closely related to the subjective response. The correlation coefficients describing the closeness of the relationship were all similar.

Table 2 also illustrates that there are close linear relationships between the Discomfort ratings and several of the respiratory timing variables. The inspiratory time, whether expressed in absolute time (T_i) (Fig. 1) or as the duty cycle ($T_i:T_{tot}$), showed the closest relationship with Discomfort. Expiratory time and total cycle time also appear to be related to Discomfort,

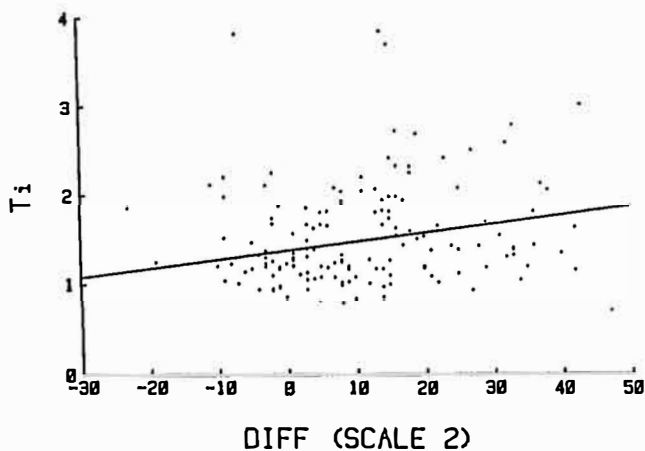


Figure. Relationship between subjective response and inspiratory time. Subjective response to respirator load (expressed as DIFF2) is shown on the x axis, and inspiratory Time (seconds) is shown on the y axis. Data from all periods with loads are shown. The solid line is the least-squares regression line.

TABLE 1
Protocols*

Protocol 1 (n = 14)
No load
Dead space† + medium inspiratory load‡
Dead space + medium expiratory load
Dead space + medium inspiratory + low expiratory load
Protocol 2 (n = 15)
No load
Dead space + medium inspiratory load
Dead space + low inspiratory load
Dead space + high inspiratory load
Protocol 3 (n = 5)
No load
Dead space + medium inspiratory load
No dead space + medium inspiratory load
No dead space + medium expiratory load
Protocol 4 (n = 13)
No load
Dead space + medium inspiratory load
High dead space
High dead space + medium inspiratory load
Protocol 5 (n = 5)
No load
Dead space + medium inspiratory load
Disposable face mask
Full-face mask cartridge

* Order of periods in each protocol was randomly varied.

† Dead space: low = 200 mL, high = 300 mL.

‡ Resistances (in cm H₂O/L/s): low = 2.02, medium = 5.64, high = 9.02.

although the relationship is not as consistently seen as with T_i and $T_i:T_{tot}$. Experimental conditions which lead to prolongation of the inspiratory phase produce increased discomfort.

The relationship between peak flow rate and subjective effect was less than the degree of association between the pressure/work-related variables and subjective tolerance.

Although there were close relationships between respiratory timing and response on scale 2 (Discomfort),

TABLE 2
Relationship between Physiologic Variables and Respiratory Sensation*

VARIABLE	Scale 1 (Time Limit)		Scale 2 (Discomfort)	
	ALL	DIM	ALL	DIM
P_{max-i}	-.31†	-.27‡	+.30‡	+.27‡
P_{avg-i}	-.29†	-.29‡	+.29†	+.28‡
$P \times T$	-.32†	-.27‡	+.34†	+.32‡
W_{max-i}	-.29†	-.27§	+.25†	-.19‡
W_{tot}	-.33†	-.29‡	+.32†	+.26§
VT	-.16§	-.21	+.18‡	+.29‡
V_i	NSR¶	NSR	NSR	NSR
RR	NSR	NSR	NSR	NSR
T_{tot}	-.09	-.08	+.20	+.32‡
T_i	-.13§	-.11	+.21†	+.32‡
$T_i:T_{tot}$	-.05	-.01	+.17‡	+.29‡
T_o	-.06	-.03	+.16‡	+.29‡
F_{max-i}	-.00	-.15	-.03	+.25§
F_{avg-i}	-.00	-.16	-.02§	+.24§

* Physiologic variables and scales are defined in the "Methods" section. ALL = all periods combined, DIM = deadspace and moderate inspiratory resistance. Numerical values are the correlation coefficients.

† $P < .01$.

‡ $P < .05$.

§ $.05 < P < .10$.

|| Not significant.

¶ NSR, no significant relationship with either scale.

TABLE 3

Relationship between Psychophysical Load Sensitivity and Respiratory Sensation*

	LSS-P		LSS-R	
	ALL	DIM	ALL	DIM
Scale 1 (Time limit)	-3.66†	-1.93‡	-10.8§	NS
Scale 2 (Discomfort)	5.86§	7.18†	18.00§	20.3‡

* Values for scales 1 and 2 represent differences from rating with no load. LSS-P = load scale sensitivity based on mouth pressure, LSS-R = load scale sensitivity based on added resistance. Regression coefficients of subjective response on LSS are shown. Statistical significance tests that coefficients are non-zero are shown.

† $.05 < P < .10$.

‡ $P < .05$.

§ $P < .01$.

|| NS, not significant.

there were no clear relationships to scale 1 (Time Limit) responses. The lack of relationship does not appear to have occurred due to inadequacy of scale as a measuring instrument since the ventilatory work measures are as closely related to scale 1 as to scale 2 responses. Thus, changes in discomfort but not in perceived work ability appear linked to respiratory timing.

A person's characteristic psychophysical load sensitivity (LSS) is also related to subjective tolerance of respiratory type loads, as seen in Table 3. For scale 1, a positive association would indicate that more highly sensitive persons tend to have less subjective intolerance (ie, are able to continue exercising longer), whereas for scale 2, a positive association means that load sensitivity is associated with more subjective discomfort. Table 3 shows that the correlation coefficients are similar whether based on LSS-P or LSS-R, and concordant results are present for both the Time Limit and Discomfort scales.

The increment in subjective intolerance due to the respiratory loads is greater in persons with high psychophysiological load sensitivity. Each subject's LSS was determined separately from the respirator loading periods, and assignment to respirator load types was random. Therefore, the observed relationships between LSS and subjective tolerance are unlikely to be artifactual. Furthermore, the relationships were present in the individual subgroups as well as in the combined data.

To investigate the manner in which the ventilatory work, respiratory timing, and load sensitivity combined are determinants of subjective tolerance, multiple regression techniques were employed. Results are summarized in Table 4. The subjective responses were treated as dependent variables, and P_{max-i} , T_i , and LSS-P were treated as predictors. These were chosen to include one variable from each of the groups shown in the simple bivariate analyses to be related to subjective tolerance. Consistent results are seen in Table 4. Ventilatory work and load sensitivity appear to be significantly related to the subjective measures, and the direction of the relationships is the same as found with the single variable analyses. T_i was correlated with P_{max-i} and, therefore, may have failed to show a significant coefficient in the multiple regression because of the closer relationship of P_{max-i} with subjective tolerance.

Discussion

To be effective in permitting safe work in a toxic atmosphere, a respirator must not itself produce significant adverse effects. Such effects might in themselves produce harm or might contribute to poor worker compliance with respiratory use, allowing toxic exposure to occur.¹⁸ The sensation of tolerance of respirators^{7, 10, 19, 20} seems to have received less research attention than have the physiologic effects, although perceived exertion during unloaded exercise is very much affected by ventilatory demands.^{19, 21} This current study was conducted to verify that there actually is a relationship between physiologic effects and subjective tolerance. Furthermore, this study demonstrates that a person's

psychophysical load sensitivity (LSS) affects the manner in which respiratory loads are perceived.

Table 2 demonstrates that subjective intolerance and the added ventilatory load imposed by a respirator are linearly related. The added work of breathing appears to affect both the perception of ability to continue exercise (Time Limit, scale 1) and the actual degree of discomfort (scale 2). This relationship was present when all loads were considered and in the "standard" respirator surrogate (DIM) periods, indicating that the effect of a single respirator load may differ among persons. Differences in respiratory pattern affect the degree to which the ventilatory work is increased and the degree of subjective intolerance due to the respirator. Hence, it is not surprising that some workers may be more bothered than others by any particular respirator type.

For the respiratory timing variables, there was a dissociation between effects on the two subjective rating scales. The timing variables, which directly reflect the pattern of breathing, showed relationships with the scale measuring discomfort but not with the scale based upon limitation of duration of exercise. This suggests that subjects may be able to separate consciously discomfort from actual physical work limitation. This dissociation is of potential importance in determining which respirator effects are particularly relevant for a particular work situation. For example, physical work limitation may be most important for emergency escape from an acutely toxic atmosphere, whereas subjective discomfort might be a major determinant of long-term proper respirator use for protection against inhaled toxins with only chronic or long latency effects (eg, lead, asbestos). Because scale 1 and scale 2 had equally close relationships to ventilatory work, it is unlikely that the dissociation between the scales is simply due to scale 1 being technically inadequate.

A visual analog scale, one of several possible dyspnea quantitation methods,²² was used to measure quantitatively the subjective sensation associated with the experimental conditions because it could be easily accomplished while exercising. The two scales used appeared to measure different aspects of respiratory sensation—the actual limitation of work v the subjective discomfort. The dissociation was particularly striking in view of the natural tendency to rate both together.

Many research studies have focused upon the ability to continue working with a respirator.²³⁻²⁸ Such studies may be inadequately sensitive to the full range of respirator effects since certain effects on subjective discomfort appear to be unrelated to ability to continue working.

Measurement of flow rates and volumes has been suggested as a valuable screening tool.²⁹ However, we found that the flow rates per se appeared to be very poorly related to both scales of subjective tolerance. This suggests that respiratory pattern and the actual work of breathing are sensed, but that flow (the end product of ventilatory muscle effort) is not as directly sensed. Respiratory control may be separated into two components separately describing timing and intensity (eg, flow) of breathing.^{30, 31} It thus appears that timing

TABLE 4
Effects of P_{max-i} , T_i , and LSS on Subjective Sensation*

	Regression Coefficient			MULT. R
	P_{max-i}	T_i	LSS-P	
Scale 1-ALL	-0.314†	-0.044	-0.137‡	0.3595
Scale 1-DIM	-0.348‡	-0.086	-0.170	0.4238
Scale 2-ALL	0.261†	0.060	0.207‡	0.3461
Scale 2-DIM	0.127	0.125	0.261	0.3573
Mean (SD)				
ALL	4.669 (3.902)	1.468 (0.540)	1.288 (0.522)	
NL	0.993 (0.245)	1.225 (0.370)		
DIM	6.815 (2.430)	1.606 (0.544)		

* Results of multiple regression analyses of subjective responses (dependent) upon maximal inspiratory pressure (P_{max-i}), inspiratory time (T_i), and load scaling sensitivity (LSS-P).

† $P < .01$.

‡ $P < .05$.

is particularly closely linked to sensation. While this study examined natural breathing patterns, other investigators experimentally forced control of breathing pattern for very short periods to assess the sensation of breathing, and have shown that volume and timing affects sensation.³²⁻³⁴ Both P_{max-i} and T_1 have been shown to affect sensation.^{33,35}

Psychophysical resistive load sensitivity is a characteristic that differs among normal persons but is consistent within persons.³⁴ As shown in Table 3, persons who have higher load sensitivity have greater subjective discomfort produced by respirator use; that is, the increment in intolerance due to respirator loads is greater. This finding was present for both scales (Time Limit and Discomfort) and was present with all periods combined and in the period common to all subjects (DIM). It is an objectively measurable variable; unlike reports of subjective sensation, LSS is unlikely to be subject to conscious manipulation. It does not reflect "tendency to complain" (eg, the threshold of subjective response) since it is measured by the relationship of increments in logarithmic sensation to increments in load rather than as the absolute value of sensation (ie, it is the slope rather than the interceptor of a stimulus-response relationship). Personality may affect LSS. In a study of asthmatics, Hudgel et al³⁶ found that personality type affected sensation of added loads, and Oswald et al³⁷ have reported relationships between personality and dyspnea.

This study has thus demonstrated that there are definite, clear relationships of subjective sensation with ventilatory work, respiratory timing, and psychophysical resistive load sensitivity. This suggests the hypothesis that respirator users adopt a breathing pattern that helps determine the ventilatory work, which in turn affects the subjective tolerance. A person's load sensitivity (a personal characteristic) may affect the respiratory pattern¹³ and affects the subjective tolerance. At least part of the pattern of adaptation is subconscious in nature.³⁸

This study thus shows that subjective tolerance is definitely related to ventilatory work and pattern of breathing. The subjective estimate of discomfort may be dissociable from the subjective estimate of ability to continue working. Persons who have high psychophysical load sensitivity may tolerate respirators relatively poorly even if they are "physiologically normal." In summary, the ability to use a respirator safely and effectively may well be determined by a combination of physiologic, psychophysical, and subjective factors.

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Life Goes On and On

... Sometimes the air is awfully clear here. You can look off to sea and see the soft, warm, raggedy roof of clouds stretching on and on and on. It almost seems as if you can look right on into eternity. The wind was blowing and the sun shown (sic) thru the leaves and dappled all the ground with light and shadow. Last nite I was down on the beach over the hill, standing on the sand at the water's edge, watching the sunset. A crab ran up a couple of feet in front of me and stopped there, and I stepped on it and smashed it in the sand for I do not like them. The sea rolled up and covered up the crab and my footprint. When it rolled back in its ceaseless motion, the sharp outlines of my footprint were gone, and the crab was completely covered. Then the sea rolled up again and back again. In the little while there was no mark upon the sand at all and the crab was nowhere to be seen. The sea rolled on, timeless in its vastness, and did not seem to care that a crab had been killed here. I thot (sic) to myself, that life is like the sea, brutal and relentless. It can't go back. It can't stand still. Therefore it must go forward. It plays the percentage. It is governed by a law of Nature. What does it matter, if some little crab or human being is smashed upon the rocks? It can't be bothered. It can't go back. It can't stand still. Therefore it must go forward, and woe be unto those, who think they may defeat it. For life, just like the sea, has never lost a battle yet. Perhaps it has been thwarted for a time, but it always comes back in the last quarter to score again, for the game has no final whistle. It ends only when you quit or cannot fight some more. —Letter to his brother Jeff by James Jones, author of *From Here to Eternity*, after learning of the death of their father.

—From "A Hunger to Write," by James Jones in *The New York Times Magazine*, March 5, 1989, p 30.