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Determinants of Pattern of Breathing During Respirator Use

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The relationship between the pattern of breathing in response to respirator-type loads and an individual's psychophysiologic sensitivity to loads (load scaling sensitivity, LSS) was investigated in the study of 11 normal volunteers. LSS was measured by having the subjects numerically rate a series of resistors; Stevens's Psychophysical Law was used to evaluate sensitivity as the slope relating log (sensation) to log (stimulus). Peak pressure and actual added resistance were the stimuli. Inspiratory time, peak pressure, duty cycle, and tidal volume were inversely related to independently measured LSS during exercise and with a respirator-type dead space and inspiratory resistance load. Because the need for changes in respiratory timing is a major adaptation in respirator use, it suggests that workers who are very sensitive to loads may have limited ability to adapt to respirator use.

Key words: respiratory control, psychophysiology, respiratory protective device

INTRODUCTION

Respirators (respiratory personal protective devices) are used by many industrial workers. Although there is considerably greater information about the physiologic strains imposed by these devices [Raven et al, 1979; James, 1976; Harber, 1984; Louhevaara, 1984], full understanding of the factors determining whether an individual will effectively use a respirator is inadequate. Identification of the factors contributing to worker tolerance or intolerance of respirators should contribute to improved medical certification methods and perhaps to improved respirator design.

A simple conceptual model can describe respirators in terms of the flow-resistive loading and the degree of rebreathing (dead space) [Harber, 1981]. The ability to utilize a respirator safely, comfortably, and effectively may be affected by more than just the ability to overcome respirator resistance. Morgan [1983] has emphasized personal psychologic characteristics in a recent review, and several investigators have focused upon workers' ability to perform several commonly used clinical pulmonary function tests [Raven et al, 1981].

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In this study, we investigated the effects of respirator use upon the pattern of breathing and sought to determine whether the nature of breathing pattern adaptation is affected by an individual's psychophysiologic sensitivity to resistances. This work sought to assess whether factors other than psychologic problems (e.g., claustrophobia, anxiety) or inability to generate pressures due to weak respiratory muscles affect ability to use a respirator. Knowing that respiratory pattern is affected by the respirator load and that there is a wide range of objectively measured psychophysical sensitivity to respiratory loads even among normal people, we sought to determine if there is a relationship between an individual's load sensitivity and his/her respiratory pattern when breathing through a respirator load. Demonstration of such a relationship would support the importance of nonmuscular determinants of respirator tolerance.

METHODS

Eleven subjects known to be free of pulmonary or cardiac disease were studied. Their ages ranged from 20 to 42 years, and the average age was 28.5. Eight were male. Each individual underwent a limited physical examination and signed a UCLA Human Subjects Protection Committee approved Informed Consent Statement after full explanation of the study and the methods involved. A period of becoming accustomed to the apparatus then followed.

Measurements made during the experimental periods are summarized in Table I. However, the order was randomized between subjects, some of whom received the "loaded" periods before the "unloaded" periods. Steady-state measurements were made during periods of 6 to 8 minutes' duration. Respiratory measurements were made during the last 30 seconds of each period. This report is based upon these steady-state periods. In addition to the steady-state measurements, each subject participated in a rapidly incremental exercise protocol immediately following the steady-state periods; in such rapidly incremental protocols, the level of exercise was increased every minute until predicted maximal heart rate was achieved or until the subject felt very uncomfortable. There was a rest period between the loaded and unloaded sections of this study.

Respiratory loads included inspiratory resistance, expiratory resistance, and dead space. The resistance element employed for both inspiration and expiration was a single acid-mist respirator cartridge (MSA, Pittsburgh, PA); its pressure-flow characteristics were linear in the range 0.3 to 2.0 liter/sec, and resistance was approximately 6 cm/liter/sec. The dead-space load was a 300-ml cylindrical tube

TABLE I. Experimental Protocol—Steady-State Periods

Period	Exercise	Resistance[a]	Dead space[b]
1	Rest	None	None
2	Rest	Inspiratory	300 ml
3	Rest	Expiratory	300 ml
4	3.5 mi/hr @ 7.5% grade	None	None
5	3.5 mi/hr @ 7.5% grade	Inspiratory	300 ml
6	3.5 mi/hr @ 7.5% grade	Expiratory	300 ml

[a]A resistance element was added to the inspiratory or expiratory limbs as shown.
[b]Dead space was added between the valve and mouthpiece.

(diameter = 1.5 cm) placed between the mouthpiece and the one-way breathing valve.

Subjects were studied at rest or at exercise of 3.5 miles per hour with 7.5% grade on a treadmill (Quinton, Seattle, WA). All subjects were able to successfully complete the study. Figure 1 summarizes the experimental apparatus. Subjects breathed through a mouthpiece connected to a Koegel valve which directed inspiratory and expiratory air flow. A Fleisch #3 pneumotachograph was placed in the inspiratory limb to measure air flow using a pressure transducer (Validyne MP-45, Northridge, CA; Hewlett-Packard 8805 amplifier, Corvallis, OR). Mouth pressure was determined from a tap in the mouthpiece with a transducer-amplifier (Validyne MP-40; Validyne demodulator; Hewlett-Packard 8802 amplifier). End tidal carbon dioxide concentration was monitored from another mouthpiece tap; and mixed expiratory gas was sampled after passing the expired gases through a large mixing chamber; oxygen, nitrogen, and carbon dioxide gas tensions were measured with a respiratory mass spectrometer (Perkin-Elmer 1100, Pomona, CA). Electrocardiogram was monitored and heart rate determined with a cardiotachometer (Quinton, Seattle, WA).

Flow and pressure data were collected with an analog digital converter (Hewlett-Packard 47310A, Corvallis, OR) at a rate of 50 Hz. Data collection was accomplished by a microcomputer system (Hewlett-Packard 9816 and disk drive 82901, Corvallis, OR). End tidal carbon dioxide tension was determined from the highest CO_2 measurement during a 30-second sampling period. In addition, mixed expired gas tensions were analyzed at the end of each period. Heart rate represents the average over the 30-second data-collection period.

Data were analyzed using programs developed for these studies. The data were graphically viewed to assure general validity. Thereafter, calculations were performed to determine respiratory timing, pressures, flows, and volumes. The beginning and end of each breath was performed by computer's algorithm. For each respiratory cycle, inspiratory time (T_i) and total time (T_{tot}) were determined, and expiratory time was calculated as their difference. The duty cycle (T_i:$T_{tot,\ DC}$) was the ratio of inspiratory to total time for a breath. The mean inspiratory flow rate was calculated as the ratio of the tidal volume to the inspiratory time (i.e., average inspiratory flow, V_t:T_i). These were then averaged for the entire data-collection period with appropriate adjustment for incomplete breaths at the beginning and end of data collection.

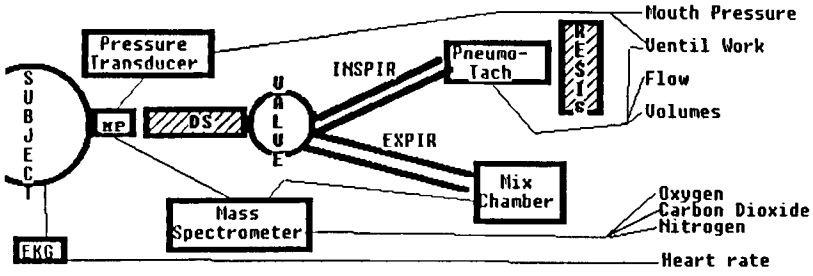

Fig. 1. The experimental apparatus is shown schematically. Components which differ among the periods (dead space, DS; added resistance, RESIS) are shown with hatch marks. The inspiratory and expiratory limbs are shown by "inspir" and "expir," respectively. MP = mouthpiece; EKG = electrocardiographic monitor.

Peak inspiratory mouth pressures ($P_{max\text{-}i}$) and average mouth pressures ($P_{avg\text{-}i}$) were also determined for each breath and averaged for a data collection. Corresponding expiratory pressures were also determined. The inspiratory pressure time integral (P_{xTi}) was also determined.

External inspiratory ventilatory work (to overcome the external resistance imposed) was calculated as the time integral of pressure times flow for each inspiration ($W_{tot\text{-}i}$). The maximum instantaneous work rate ($W_{max\text{-}i}$) was calculated as the product of maximal inspiratory flow rate ($F_{max\text{-}i}$) and maximal inspiratory mouth pressure. Tidal volume (V_t) and inspiratory minute volume (V_i) were determined by integrating the flow signal.

Oxygen consumption (VO_2) and CO_2 production (VCO_2) were expressed in standard temperature and pressure (STP) terms. End tidal carbon dioxide tension ($PetCO_2$) was determined from the mass spectrometer. Heart rate (HR) is shown as beats/minute.

Magnitude estimation of added inspiratory resistances [Stevens, 1975; Killian et al, 1981], herein called load scaling, was performed several times (see Table I): twice at rest with no load; once at exercise with no load; once at rest with inspiratory load; and once at exercise with inspiratory load. The technique was explained in detail to the subject before initiating the study; subjects were asked to choose a number (using any scale they chose) to describe the resistance that they felt. For each load-scaling set, a series of 12 inspiratory resistances were interposed in the breathing circuit in random order for two breaths each, separated by several unloaded breaths. Subjects were carefully instructed not to change the respiratory pattern during load-scaling studies. In each instance, the resistance was announced, and the subject was asked to write a number describing how much resistance he/she felt. No a priori scale was suggested to the subject. Resistances were constructed of fine wire mesh, cotton filters, and paper filters; these were encased in a series of four-inch plastic pipes. For load scaling, the inspiratory limb of the breathing circuit was connected to one limb of a large Y connector. The resistance elements could be placed in another limb, and the third limb had a DuBois shutter. This allowed resistance to be placed with impeding inspiratory air flow as long as the DuBois shutter was open; when activated by the researcher, the shutter closed, forcing inspiratory air flow to occur through the resistance element. The highest resistance element was presented in the beginning and in the middle of each set to provide perspective for the subject. The resistances ranged from 2 to 26 cm of water per liter/sec and were approximately linear in the flow ranges employed. The peak mouth pressure generated during breathing through each resistance was recorded from a paper recording.

For each set, the load scaling sensitivity (LSS) was determined in two fashions, once using peak mouth pressure (LSS-P) and once with the actual resistance (LSS-R) as the stimulus variable for each breath. The numeric score assigned for each resistance was used as the response variable. A least squares linear regression analysis of the logarithm of the response upon the logarithm of the stimulus was performed; the slope of the regression line represents the sensitivity (LSS-P or LSS-R). In a few instances, one or two points were obvious outliers, often representing obvious inattention of the subject to a particular resistance; the technician performing the calculations could eliminate up to two such points from each set if the points' residual difference from the calculated regression line was at least three times the overall mean residual. In general, identification of such points was quite obvious graphically. In addition to

calculating the two slopes (log of response vs. log of pressure and log of response vs. log of actual added resistance), the correlation coefficient for each of the lines was determined. A load scaling sensitivity value was discarded if the correlation coefficient was less than 0.6. The values for the five repetitions for each subject were then averaged to arrive at a summary LSS-P and summary LSS-R for the subject. There was a close relationship between the summary LSS-R and summary LSS-P for each subject; the correlation coefficient was 0.84.

Analysis of variance was used to determine if there was an effect of exercise, of respiratory load, and of an interaction between load and exercise [Dixon, 1983]. Analyses with linear contrasts were performed to separate the effect of exercise and of load [Dixon, 1983]. In addition, linear regression analyses were performed to determine the relationship between load scaling sensitivity and respiratory pattern parameters. All statistical calculations were performed using BMDP programs on a personal computer (IBM XT).

RESULTS

Table II summarizes the physiologic variables for each of the experimental periods.

It may be seen that the addition of an inspiratory resistive and dead-space respiratory load produced increases in all of the measures of the external inspiratory work of ventilation. Work was determined in two fashions. First, measures related to mouth pressure are related to the force exerted by the respiratory muscles; and second, the work terms are related to the actual work accomplished (expressed as the pressure-volume product) in moving air across the external resistance. Total work performed ($P \times T$, W_{tot}), average work rate ($P_{avg\text{-}i}$, W/t), and peak work rate ($P_{max\text{-}i}$, $W_{max\text{-}i}$) were all similarly affected. There were statistically significant interactions between the level of exercise and the measures of work, implying that the effect of the respirator load was proportionately greater at higher exercise levels.

Respiratory timing was also affected by inspiratory loading in a manner comparable to that shown in previous studies [Harber et al, 1982]. Inspiratory time, the duty cycle (T_i:T_{tot}), and mean inspiratory flow rates all decreased. Possibly because of the small number of subjects, these effects did not reach statistical significance. Expiratory resistive loading led to a nonstatistically significant increase in expiratory time. In addition, expiratory loading led to an increase in tidal volume, but there was no clinically or statistically significant effect on end tidal CO_2 tension, suggesting that hyperventilation did not occur. With expiratory resistive loading, the increase in tidal volume was approximately equal to the magnitude of the added dead space. With inspiratory loading, there was also an increase in the tidal volume, but statistical significance was not achieved in this study.

The relationship between measures of psychophysiologic sensitivity to added resistance and the pattern of breathing is summarized in Table III. Group means and standard deviations for LSS are shown for the experimental periods in which such measurements were made. The overall mean LSS determined by added resistance was 0.340 (standard deviation = 0.10), and the overall mean LSS based upon pressure was 1.207 (S.D. = 0.36). Table III also shows the regression coefficients relating LSS and the physiologic variables; in addition, the p values for the coefficients being nonzero are shown. Coefficients whose p values are >0.15 are not shown. The

TABLE II. Physiologic Variables*

	Period						ANOVA			Contrasts	
	1	2	3	4	5	6	LD	EX	IN	I	E
Exercise	R	R	R	E	E	E					
Load	—	I	E	—	I	E					
Pressures											
Max-i	1.09	4.16	1.32	2.01	9.49	2.06	[b]	[b]	[b]	[b]	—
Avg-i	0.85	3.13	0.98	1.34	6.91	1.42	[b]	[b]	[b]	[b]	—
PxT-i	1.15	4.68	1.50	1.42	9.23	1.77	[b]	[b]	[b]	[b]	—
External work											
$W_{max\text{-}i}$	0.72	3.04	1.24	3.56	14.11	3.81	[b]	[b]	[b]	[b]	—
$W_{tot\text{-}i}$	0.57	2.59	0.99	1.97	11.10	2.43	[b]	[b]	[b]	[b]	—
$W/_{T\text{-}i}$	0.43	1.78	0.69	1.85	8.44	2.11	[b]	[b]	[b]	[b]	—
Timing											
T_i	1.42	1.61	1.59	1.12	1.45	1.35	—	+	—	—	—
T_{tot}	4.15	4.33	4.85	2.64	2.76	3.34	—	[b]	—	—	—
DC	0.44	0.53	0.40	0.34	0.38	0.42	—	[b]	+	—	—
V_i:T_i	0.45	0.46	0.60	1.22	1.06	1.26	[a]	[b]	—	—	—
RR	15.76	15.08	14.41	24.76	23.05	20.40	—	[b]	—	—	—
Te	2.86	2.83	3.34	1.59	1.42	2.10	—	[b]	—	—	—
$F_{max\text{-}i}$	0.57	0.59	0.79	1.57	1.31	1.59	[a]	[b]	—	—	—
Ventilation											
V_t	0.63	0.74	0.93	1.37	1.51	1.60	[a]	[b]	—	—	+
V_i	9.43	11.11	12.19	31.64	33.53	30.33	—	[b]	—	—	—
$PetCo_2$	30.25	35.17	36.43	41.42	42.90	42.48	[b]	[b]	+	—	—
Metabolic											
VO_2	0.22	0.23	0.23	1.29	1.16	1.17	—	[b]	—	—	—
VCO_2	0.23	0.20	0.22	1.28	1.14	1.91	—	[b]	—	—	—
HR	87.15	92.58	96.25	120.66	126.66	116.22	—	[b]	—	—	—

*Group mean physiologic variable results are shown. Exercise level is denoted by R = rest, E = exercise. The loads included: I = inspiratory resistance and dead space; E = expiratory resistance and dead space. Results of analyses of variance (ANOVA) are shown for main effects of load (LD) and of exercise (EX) as well as for their interaction (IN). Linear contrasts compared inspiratory loads vs. no load (I) and expiratory loads vs. no load. p values are summarized as follows: −: $p > .10$; +: $.05 < p < .10$;[a]: $p < .05$; [b]: $p < .01$.

TABLE III. Relationship Between Load Sensitivity and Voluntary Breathing Pattern

	By resistance				By pressure			
Exercise Resp. load	Rest none	Rest load[a]	Ex none	Ex load	Rest none	Rest load	Ex none	Ex load
LSS (mean)[b]	.362	.283	.346	.247	1.09	1.10	1.25	1.16
Standard dev.	.12	.12	.10	.16	.27	.31	.63	.73
T_i (sec)		−2.56 (.05)						
$P_{max\text{-}i}$				−12.4 (.12)				
$F_{avg\text{-}i}$			−1.17 (.10)	−1.10 (.058)				
Duty cycle			−1.17 (.10)	−1.12 (.06)				
Tidal vol.	−1.61 (.045)	−1.63 (.005)	−2.00 (.13)	−2.75 (.10)	−.324 (.10)			

[a]"Load" refers to an inspiratory resistance and dead-space load (see Table I).

[b]The means and standard deviations for LSS (load scaling sensitivity) based upon added resistance or pressure for each period are shown. The regression coefficients relating the breathing pattern variable to the sensitivity resistance (LSS) are shown in the table. p-values for the coefficients are shown in parentheses.

pattern of breathing was measured independently of the measurement of LSS. The two measures of LSS—based on pressure and on actual resistance—were closely related in individuals ($r = .86$, $p < .01$). Subjects who were sensitive to added resistances chose breathing patterns with relatively low maximal inspiratory pressure and relatively short inspiratory times. In addition, persons who were sensitive to resistance had lower tidal volumes. The relationships were closest during periods of inspiratory loading and during exercise.

DISCUSSION

The reasons why some individuals find it particularly difficult to use respiratory personal protective devices (respirators) are poorly understood [Harber, 1984; Louhevaara, 1986; NIOSH, 1976]. Such workers' inability to tolerate the device may preclude placement in an industrial setting with potential toxic exposure. Several studies of respirator effect have primarily focused on physiologic factors [Hodous et al, 1983], and poor tolerance has been considered possibly psychological [Morgan, 1983].

The pattern of breathing adaptation to inspiratory flow-resistive and dead-space loading in this study was similar to that observed in earlier studies [Raven et al, 1982; Lerman et al, 1983; Harber et al, 1982; James, 1976; Raven et al, 1979; Bentley et al, 1973]. The inspiratory time was prolonged and the duty cycle (proportion of the respiratory cycle in which the respiratory muscles were active) was increased. The peak and average inspiratory flow rate were, however, decreased. In this manner, the average and maximal work rates to overcome the external respiratory load were lower than if no adjustment of respiratory pattern had occurred, decreasing the energy cost of breathing [Mead, 1979]. Axen et al [1984] have shown significant differences in patterns of load compensation among individuals, and Love et al [1977] found significantly different responses to CO_2 loads. Interpersonal differences in respiratory pattern may partially explain differences in respirator tolerance; the expiratory load had less consistent effects on the respiratory pattern. The data concerning expiratory flow-resistive loading collected in this study are being combined with data from other studies and will be reported separately.

This study demonstrates that there is a relationship between breathing pattern and an individual's psychophysiologic sensitivity to added resistive loads when stressed by an inspiratory load and exercise. The subjects who breathe with relatively lower peak pressures have shorter inspiratory times (T_i and duty cycle), and lower tidal volumes tend to have greater sensitivity to added loads when this was measured independently. This tendency of sensitive individuals to minimize the sensation of the external resistance is consistent with several previous physiologic studies which have shown that the pattern of breathing during load scaling testing is one determinant of the magnitude of the sensation [Stubbing et al, 1983; Killian et al, 1982; Burki, 1984]. Respiratory timing is regulated independently of flow [Milic-Emili, 1982] and may be closely related to sensation. Our findings suggest that a psychologic personal characteristic, load sensitivity, is a nonmechanical determinant of breathing pattern when the respiratory system is stressed. Load sensitivity effects may complement optimization of respiratory work [Otis et al, 1950] and of energy cost [Mead, 1960].

The load-sensitive individual may tend to limit the length of time over which the inspiratory muscles are active, thus preventing the normal prolongation of inspi-

ration due to a respirator load. Thus, the previously unexplained observations that some workers with apparently normal pulmonary function are particularly intolerant of respirators might be explained if such individuals were particularly load sensitive. While this current study supports this hypothesis, direct confirmation would require study of a large population of respirator users to determine if there is indeed an empiric relationship between subjective complaints and objectively measured psychophysiologic load sensitivity.

Our study design differs significantly from previous experimental studies investigating the relationship between sensitivity and breathing pattern in normal volunteers, which sought to determine which characteristics of a breath affected the sensation associated with that specific breath. Our current study, however, investigated whether a person's spontaneous breathing pattern reflected his/her load sensitivity. The latter is a personal chracteristic which differs considerably even among "normal" persons [Killian et al, 1981] but which is stable over time in an individual. Oliven et al [1985] showed that chronic obstructive pulmonary disease (COPD) patients who were load sensitive tended to hypoventilate and have lower V_t's when forced to breathe through an external resistance.

Load sensitivity was measured objectively. The LSS is measured based upon the slope of the stimulus-response relationship rather than upon the intercept or mean response, and hence, persons who simply have a tendency to complain about discomfort would not be found to have high load scaling sensitivity. Thus, this study suggests that there truly is an objective, involuntary relationship between an individual's "psychology" and his/her physiologic adaptation to respirator use.

Load sensitivity was measured based upon two different, but closely related, stimuli—the actual added resistance and the peak mouth pressure. The two measures showed a very close correlation in this study. In earlier studies, Burki [1984] suggested that pressure, rather than resistance, was sensed, but in this study which focused upon the longer-term relationship, resistance sensation appears equally important. Sensation of resistance per se has also been seen in a study of load detection [Killian et al, 1979].

CONCLUSIONS

In summary, this study has shown that a psychophyiologic characteristic of an individual affects breathing pattern in a manner which in some individuals may interfere with normal adaptation to respirator use. Although preliminary, these results suggest a possible basis for unexplained poor tolerance of respirators by some workers. Furthermore, these findings suggest that respiratory pattern, in addition to muscular ability to generate air flow, may be an important parameter to consider in medically evaluating workers for respirator use [Raven et al, 1979; Boehlecke, 1984; Harber, 1984; Louhevaara, 1984]. Load scaling sensitivity per se is a technique that is unlikely to be useful except in research settings, but respiratory timing (shown by the regressions to be a predictor of load sensitivity) can be easily measured in field settings. An individual's load sensitivity should be added to the list of "respirator user's strains" proposed by Louhevaara [1986].

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REFERENCES

Axen K, Haas F, Gaudino D, Haas SS (1984): Effect of mechanical loading on breathing patterns in women. J Appl Physiol 56:175–81.

Bentley RA, Griffin OG, Love R, Muir DC, Sweetland KF (1973): Acceptable levels for breathing resistance of respiratory apparatus. Arch Environ Health 27:272–280.

Boehlecke B (1984): Respiratory protection. In Morgan WKC and Seaton A (eds.): "Occupational Lung Diseaes." Philadelphia; Saunders.

Burki NK (1984): Effects of bronchodilation on magnitude estimation of added resistive loads in asthmatic subjects. Am Rev Respir Dis 129:225–229.

Dixon WJ (ed) (1983): BMDP Statistical Software. University of California Press.

Harber P (1981): Prevention and control of occupational lung disease. In Brooks SM, Lockey JE, Harber P (eds): "Clinics in Chest Medicine," 2nd ed. Philadelphia: WB Saunders, pp. 343–356.

Harber P (1984): Medical evaluation for respirator use. J Occup Med 26:496–502.

Harber P, Tamimie J, Bhattacharya A, Barber M (1982): Physiologic effects of respirator dead space and resistance loading. J Occup Med 24:681–689.

Hodous TK, Petsonk L, Boyles C, Hankinson J, Amandus H (1983): Effects of added resistance to breathing during exercise in obstructive lung disease. Am Rev Respir Dis 128:943–948.

James RH (1976): Breathing resistance and dead space in respiratory protective devices. Cincinnati: National Institute of Occupational Safety and Health.

Killian KJ, Bucens DD, Campbell EJH (1982): Effect of breathing patterns on the perceived magnitude of added loads to breathing. J Appl Physiol 52:578–584.

Killian KJ, Campbell EJM, Howell JBL (1979): The effects of increased ventilation of resistive load discrimination. Am Rev Resp Dis 120:1233–38.

Killian KJ, Mahutte CK, Campbell EJM (1981): Magnitude scaling of externally added loads to breathing. Am Rev Resp Dis 123:12–15.

Lerman Y, Shefer A, Epstein Y, Keren G (1983): External inspiratory resistance of protective respiratory devices: Effects on physical performance and respiratory function. Am J Ind Med 4:733–740.

Louhevaara VA (1984): Physiologic effects associated with the use of respiratory protective devices. A review. Scand J Work Environ Health 10:275–281.

Louhevaara VA (1986): Respirator wearer's strain: A complex problem. Am J Ind Med 10:3–6.

Love RG, Muir DC, Sweetland KF, Bentley RA, Griffin OG (1977): Acceptable levels for the breathing resistance of respiratory apparatus: results for men over the age of 45. Br J Ind Med 34:126–129.

Mead J (1960): Control of respiratory frequency. J Appl Physiol 15:325–336.

Mead J (1979): Responses to loaded breathing. A critique and a synthesis. Bull Europ Physiopath Resp 15:61–71.

Milic-Emili J (1982): Recent advances in clinical assessment of control of breathing. Lung 160:1–17.

Morgan WP (1983): Psychological problems associated with the wearing of industrial respirators: A review. Am Ind Hyg Assoc J 44:671–676.

NIOSH (1976): "A Guide to Industrial Respiratory Protection." (NIOSH publication 76–189) Department of Health, Education and Welfare.

Oliven A, Kelsen S, Deal E Jr., Cherniack N (1985): Respiratory pressure sensation: Relationship to changes in breathing pattern and PCO_2 during acute increase in airway resistance in patients with Chronic Obstructive Pulmonary Disease. Am Rev Resp Dis 132 (6):1215–1218.

Otis AB, Fenn WO, Rahn H (1950): Mechanics of breathing in man. J Appl Physiol 2:592–607.

Raven PB, Bradley O, Rohm-Young D, McClure FL, Skaggs B (1982): Physiological response to "pressure-demand" respirator wear. Am Ind Hyg Assoc J 43:773–781.

Raven PB, Dodson AT, Davis TO (1979): The physiological consequences of wearing industrial respirators: A review. Am Ind Hyg Assoc J 40:517–534.

Raven PB, Moss RF, Page K, Garmon R, Skaggs B (1981): Clinical pulmonary function and industrial respirator wear. Am Ind Hyg Asssoc J 42 (12):897–903.

Stevens SS (1975): On the psychophysical law. Psychol Rev 64:153–181.

Stubbing DG, Ramsdale EH, Killian KJ, Campbell EJM (1983): Psychophysics of inspiratory muscle force. J Appl Physiol 54:1216–1221.