Relative Effects of Flow-Resistive and Pressure-Biased Respiratory Loading

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The effects of pressure-biased breathing (PBB), which simulates positive pressure respirator use, were studied in 15 volunteer subjects during laboratory exercise. PBB was compared with inspiratory resistance: dead space (ID) load and a no-load (N) situation. PBB had adverse subjective effects comparable with those of ID. Physiologically, PBB led to a small decrease in inspiratory time and an increase in expiratory time as well as an increase in the intensity of ventilatory effort as measured by the mean inspiratory flow rate. It is postulated, based on these findings, that PBB has significant effects on the resting lung volume, leading to both physiologic and subjective consequences.

Respirators impose several types of physiologic loads. These include inspiratory air-flow resistance, dead space (rebreathing volume from the mask), expiratory flow resistance, thermal loading, carrying the weight of the device, and others. The magnitude of each load, however, is dependent on the respirator design and use. Several studies have investigated the effects of these loads individually and in combination. An additional type of respirator physiologic load is unique to the respirators used under the most hazardous situations. In such instances, the worker must be protected against even trace inhalation. To assure that no toxin enters through a small leak, the respirator is designed to operate in a positive pressure mode, commonly termed pressure-demand. In this manner, the pressure within the faceplate (mask) is always kept positive to the surrounding atmosphere, so that even if a small leak were present, the net flow would be from inside to outside the mask.

Positive pressure breathing does impose an additional load on the respiratory system. Here, unlike the normal situation, the pressure at the mouth does not decline to reach atmospheric levels at the end of a normal respiratory cycle. Rather, there is a positive end expiratory pressure (PEEP). Because "PEEP" is commonly used in medicine in an intensive care unit context, the physiologic term "pressure-biased breathing" (PBB) will be used to describe this phenomenon here. There are similarities and differences between intensive care unit ventilator PEEP and respirator-induced PBB; these are considered in the discussion.

This study examines the physiologic and subjective effects of PBB induced by experimental respirator surrogates and compares these with the effects of the more typical dead space and resistance loading.

Methods

The research project was one in a series designed to elucidate the effects of respirator loads. The study was approved by the University of California, Los Angeles, Human Subject Protection Committee, and each volunteer gave informed consent before participation. Subjects, who were paid a nominal fee for participating, included 8 men and 7 women, aged 20 to 39 (mean = 29.5 years). (Because of technical problems in the multiple recording systems used, the subject number for each variable may differ if data were inadvertently lost.) Each subject had a medical history taken and received an examination to assure fitness before participation.

The protocol included up to 5 weeks of study. During the course of these studies, subjects were tested in an experimental laboratory setting and in a field setting with a variety of loads. This report describes the findings

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0096-1736/91/3310-1055$3.00/0

from the study component in the exercise laboratory setting for two sessions. The order of the experimental sessions was constant for the subjects, but the period order within a session was randomized.

The studies were all performed at an exercise rate of 50 to 60 W on a calibrated bicycle ergometer (Monarch, model 818, Varberg, Sweden). Subjects breathed through a mouthpiece and wore a noseclip for these studies. Physiologic recording methods and subjective response determination were similar to those used in previous studies.[1] Table 1 summarizes the variables measured. Inspiratory air flow was measured with a pneumotachograph (Fleisch, number 3) pressure transducer (Validyne, MP-5, Northridge, CA). Pressure at the mouth was measured from atop in the mouthpiece (Validyne MP-45). End tidal CO_2 was determined with a respiratory mass spectrometer (Perkin Elmer 1100, Pomona, CA). Signals were conditioned (Hewlett Packard 7754A, 7754B) and digitized at 50Hz (Hewlett Packard 47310A A/D converter and HP9816 microcomputer, Corvallis, OR). The physiologic variables were calculated with programs specifically developed for these purposes.

Several types of respirator surrogate loads were used. Dead space consisted of a cylindrical 200 mL placed between the one-way Otis-McKerrow valve (WE Collins, Braintree, MA) and the mouthpiece. Inspiratory flow resistance was produced by a single respirator cartridge (MSA Acid-Mist, Pittsburgh) placed in the inspiratory line. End expiratory pressure (PBB) was created by inserting a nominal 5 cm PEEP valve in the expiratory line. This valve is a commercially available model commonly used in critical care units to add PEEP to ventilator patients (Vital Signs, Totowa, NJ). It operates with a calibrated spring-loaded device that is occluded when back pressure falls to 5 cm water. This effectively allows the production of a known minimal end expiratory pressure without directly affecting loading at other times. In this study, the effects of three types of loads are described: no load (N), combined inspiratory resistance and dead space (ID), and pressure-biased breathing (PBB).

TABLE 1
Variables Studied

Respiratory volumes
V_I: inspiratory minute ventilation (L/min)
V_t: tidal volume (L)
Respiratory pattern
T_i: inspiration time (sec)
T_e: expiration time (sec)
F_{avgi}: average inspiratory flow rate (Vt/TI)
F_{maxi}: peak inspiratory flow rate (L/sec)
T_i/T_{tot}: duty cycle (fraction of cycle devoted to inspiration)
RR: respiratory rate (min^{-1})
$P_{et}CO_2$: End tidal CO_2 tension (mm Hg)
Added work of breathing
P_{maxi}: peak inspiratory pressure (cm H_2O)
P_{avgi}: average inspiratory pressure (cm H_2O)
P_{maxe}: peak expiratory pressure (cm H_2O)
P_{avge}: average expiratory pressure (cm H_2O)
P × T: pressure time integral (inspiratory) (cm $H_2O \cdot$sec)
W_{tot}: total external work of inspiration (calculated as the pressure volume integral)
W_{maxi}: peak inspiratory work rate (calculated as $P_{maxi} \times P_{maxi}$)
Subjective response
Exert: "How long can you continue . . .?" (mm)
Discom: "How uncomfortable is this . . .?" (mm)

Experimental periods were approximately 6 minutes, and physiologic data were collected in the last minute to allow a steady state to be achieved. Each set of measurements was performed over two sessions.

Subjective responses were measured using two previously validated visual analog scales.[1] "EXERT" was the response to this question, "How long could you continue exercising like this?" "DISC" was the response to a question of "How uncomfortable is breathing like this?" These scales are designed so that "adverse effects" are recorded by high numbers on one scale and low on the other to encourage the subject to consider each question independently. Measurements are in millimeters from the baseline of the written form used. Subjective measures were recorded by the subjects at the very end of each experimental period to avoid any potential interference with collection of the physiologic data.

Statistical analyses were performed using BMDP programs that included descriptive statistics and analysis of variance (ANOVA) with repeated measures,[2,3] recognizing that each subject was studied under numerous conditions. Paired *t* tests were used to compare pairs of periods. A P value of $<.05$ was considered significant and a P value of $<.10$ was considered of borderline significance.

Results

The findings are shown in Table 2. The effect of respirator loads is shown by the "overall" ANOVA. Table 2 also shows the paired comparisons. The response variables measured fall into several groups; respiratory volumes, respiratory pattern, added work of breathing, and subjective responses. In general, the responses to the ID loads found in this study were similar to that noted in earlier studies[1,3-5] and therefore may serve as a valid baseline for comparison.

Among the ventilatory volumes, as would be expected, the addition of the ID load increased the tidal volume to an amount almost equal to the added dead space. PBB did not appear to significantly affect the tidal volume. Similarly, minute ventilation was largely maintained. The net effect of ventilation, elimination of CO_2 and maintenance of homeostatic blood CO_2 tension (reflected in the end tidal CO_2 concentration), showed a small but consistent effect, leading to a slight increase in the end tidal CO_2 with the ID and PBB loads. As may be seen from Table 2, the effect of PBB on CO_2 elimination appeared lower than did that of ID.

During rest and limited exercise, most of the work of breathing is inspiratory because the ventilatory muscles must actively contract, whereas expiration is largely a passive, recoil-driven process. Hence, measures of inspiratory response reflect the impact on the ventilatory work of breathing. This is measured in two general ways

TABLE 2
Effects of Pressure and Inspiratory Resistance—Dead Space Loads

Variable	Period Means			Effect of Load Comparisons							
				Overall§		ID-NL		PBB-NL		*ID-PBB*	
	NL* Mean (SD)	ID† Mean (SD)	PBB‡ Mean (SD)	F	*P*	*t*	*P*	*t*	*P*	*t*	*P*
P_{maxI}	1.14 (0.29)	8.10 (1.77)	2.56 (1.01)	130.54	0.00	16.11	‖	5.22	‖	11.16	‖
P_{avgI}	0.64 (0.19)	5.17 (1.11)	0.93 (0.40)	238.04	0.00	16.21	‖	3.02	¶	15.89	‖
P_{maxE}	1.18 (0.31)	1.62 (0.50)	6.23 (1.59)	167.07	0.00	3.60	‖	12.73	‖	−12.92	‖
P_{avgE}	0.68 (0.21)	0.64 (0.22)	4.33 (1.23)	−152.02	0.00	−1.90	#	11.89	‖	−12.70	‖
P × T	1.11 (0.40)	11.00 (3.00)	1.78 (1.11)	153.18	0.00	12.91	‖	2.45	¶	13.20	‖
W_{tot}	1.04 (0.46)	9.61 (2.89)	1.17 (0.51)	118.35	0.00	11.16	‖	1.34	**	11.64	‖
W_{maxI}	1.41 (0.43)	8.83 (2.63)	3.65 (1.85)	55.97	0.00	10.71	‖	4.93	‖	6.34	‖
W_I	24.83 (5.68)	25.59 (5.74)	23.39 (5.86)	4.73	0.02	1.16	**	−2.32	¶	2.51	¶
W_t	1.52 (0.41)	1.67 (0.35)	1.58 (0.44)	3.71	0.04	3.01	¶	1.11	**	1.45	**
F_{avgI}	0.80 (0.14)	0.73 (0.11)	0.85 (0.14)	5.39	0.01	−2.19	¶	1.34	**	−2.89	¶
F_{maxI}	1.16 (0.18)	1.02 (0.14)	1.28 (0.19)	15.84	0.00	−4.57	‖	2.28	¶	−4.92	‖
T_I	1.86 (0.44)	2.31 (0.68)	1.84 (0.54)	18.64	0.00	4.95	‖	−0.15	**	5.53	‖
T_e	2.18 (1.12)	2.01 (0.90)	2.57 (1.34)	8.73	0.00	−1.52	**	3.01	¶	−3.40	‖
T_I/T_{tot}	0.52 (0.07)	0.59 (0.06)	0.47 (0.09)	20.58	0.00	3.67	‖	−2.49	¶	7.15	‖
RR	17.71 (6.28)	16.57 (6.08)	16.25 (5.95)	4.32	0.02	−2.03	#	−2.80	¶	0.68	**
$P_{et}CO_2$	41.11 (4.82)	44.73 (4.09)	43.29 (4.50)	6.76	0.01	4.51	‖	2.55	¶	1.28	**
HR	110.16 (14.74)	112.77 (11.66)	113.09 (12.87)	2.27	0.13	1.85	#	2.08	#	−0.19	**
Exert	4.27 (1.25)	3.44 (1.02)	3.68 (0.97)	7.27	0.00	−3.54	‖	−3.64	‖	−1.17	**
Discom	2.57 (0.83)	3.68 (1.03)	3.38 (1.18)	18.06	0.00	6.52	‖	4.69	‖	1.83	#

* NL = no load.
† ID = Inspiratory resistance + dead space.
‡ PBB = pressure-biased breathing.
§ "Overall" columns show F and *P* values for load effects. The load comparisons show paired *t* tests *P* and *t* values for the indicated pairs of periods. Variables are defined in Table 1.
‖ $P < .01$.
¶ $P < .05$.
# $P < .10$.
** $P \geq .10$.

in this study: first, the work performed to overcome the external resistance is measured as the pressure-volume integral or as the pressure-time integral. Second, the mouth pressure is an indirect indicator of the force generated by the ventilatory muscles. As may be noted from Table 2, the PBB load did not lead to significant increases in the inspiratory work of breathing, although the ID load had very significant effects. Thus, it appears that PBB does not primarily lead to inspiratory loading as a cause of its physiologic impact. PBB did, however, lead to increases in both the average and peak expiratory pressures.

The respiratory pattern was influenced by both types of load but in opposite directions. That is, PBB produced a prolongation of the expiratory phase with some decrement in the inspiratory time. ID loading, however, prolonged inspiration. In general, the respiratory rate itself, reflecting the total respiratory cycle time, was not affected.

Subjectively, both the PBB and the ID loading affected the EXERT scale and the DISCOMFORT scale. The magnitude of the effects was comparable for the two distinct load types.

The ANOVA also compared the effect of week (first versus second session), and no significant effects were noted. This suggests that the effects tend to be quite consistent.

Discussion

Positive pressure respirators are designed to maintain a positive pressure within the mask at all times. When operating properly, the pressure at the mouth should never be less than the pressure at the mask.

This study demonstrated that pressure-biased breathing, which might also be called positive end expiratory pressure, had significant physiologic and subjective effects. Subjectively, PBB had effects comparable with those of an ID load. The subjective discomfort due to PBB may be particularly significant because positive pressure respirators are commonly used in situations that produce other subjective loads as well, such as thermal discomfort due to impervious clothing in hazardous waste operations, heavy exertion levels (as in fire fighting), and impaired mobility due to the physical characteristics of the device. Because positive pressure respirators are used only in the most hazardous situations, workers may be likely to try to tolerate the discomfort to a greater degree than in typical air-purifying respirator use situations. However, the subjective discomfort may modify compliance with use for carcinogens, for which the worker does not fear an immediate adverse effect.

Several consistent physiologic effects of PBB were

noted. The added expiratory pressure tended to have its major effect at the end of expiration, when it would normally have reached atmospheric pressure. As anticipated, the peak and average expiratory pressures rose. PBB, unlike ID, did not produce large changes in the tidal volume. However, it did change the respiratory pattern, leading to a prolongation of expiratory time. To the extent that PBB is an added expiratory load, it is not unexpected that expiratory time is prolonged, just as inspiratory loading tends to prolong the inspiratory time. The slight shortening of inspiratory time is probably a consequence of the prolongation of the expiratory phase. Similary, the slight increase in mean inspiratory flow rate is most likely due to the shortening of inspiratory time.

There are several mechanisms by which PBB may produce effects. First, the added expiratory pressure itself may directly increase the ventilatory work of expiration. This is likely to be particularly important in those persons with obstructive lung diseases (chronic obstructive pulmonary disease or asthma), who already face significant expiratory loading. However, such significantly impaired persons probably should not be placed in jobs requiring the use of positive pressure breathing.

Second, the indirect effect on inspiratory time may also be significant. Experimental studies during respirator use have demonstrated relationships between inspiratory time and subjective response,[6] suggesting that this variable is actually sensed. Milic-Emili[7] has demonstrated that respiratory control may be considered to have two components: a timing mechanism (that would be reflected in the inspiratory time) and an intensity control (reflected in the mean flow rate). The mean inspiratory flow rate did increase with PBB, thereby increasing the actual load and probably the sensed load on the inspiratory musculature.

A third mechanism by which PBB might affect the respiratory system is by producing a change in the functional residual capacity (FRC). This is the volume of the lung at the end of a normal respiratory cycle. Under normal circumstance, the FRC is passively determined by the mechanical properties of the lung and chest wall. It represents the volume at which the natural tendency of the chest wall to spring outward is counterbalanced by the tendency of the lung to collapse inward. By increasing the pressure at the airway, the rest position of the lung is increased in volume. (This increase in FRC is the goal of therapeutic use of PEEP in ICU ventilation of patients with the adult respiratory distress syndrome.) An increase in FRC would have potential adverse effects. For example, the pressure volume relationship of the lung is not linear; at higher lung volumes, the respiratory muscles must generate a greater pressure to achieve inhalation of any given volume. This effective decrease in compliance leads to an increase in the ventilatory work of inspiration. Furthermore, the respiratory musculature may be more inefficient when the lung volume is increased. This occurs because the diaphragm (the major inspiratory contractile muscle) increases its effective radius (flattens), making it inefficient. In addition, the respiratory muscles are normally at their optimal length-tension relationship at the normal FRC. There may be significant indirect effects of changes in FRC as well. For example, pulmonary stretch receptors may be stimulated, leading to adverse sensations.

Although the effects on lung volume and ventilation of PBB induced by industrial respirators is similar to that induced by therapeutic use of PEEP with ventilator patients, the cardiovascular effects are quite likely to be different. With respirator PBB, the user still generates a negative pleural pressure to draw air into the chest, whereas with ventilator PEEP, positive pressure is supplied by the ventilator throughout the inspiratory cycle to "force air into the lung." Thus, the ventilator PEEP creates much more of an intrathoracic positive pressure throughout the respiratory cycle than does respirator PBB. The large increase in mean intrathoracic pressure induced by ventilator PEEP significantly interferes with venous return by decreasing the venous pressure gradient from the extrathoracic to the intrathoracic areas; this leads to the well-known decrease in cardiac output after institution of PEEP in the ICU. Respirator PBB does not have this net effect. Arborelius et al[8] directly studied hemodynamics by catheterization during exercise using positive pressure respirators and demonstrated that there does not appear to be a major adverse effect.

Raven et al,[9] Wilson et al,[10] and Dahlback and Novak[11] have empirically demonstrated that during high levels of exercise, the intramask pressure may actually not always be maintained above atmospheric pressure due to high instantaneous inspiration rates. The decrease in expiratory time due to PBB may accentuate this effect by shortening inspiration time, thereby leading to increased inspiratory flows and negative pressure. It may therefore be necessary in the future to increase the level of PBB to guarantee full protection.

Several investigators have performed studies of pressure-demand respirators. Unlike this current study, which employed surrogate respirator loads to permit delineation of specific effects, the previous studies did not address the unique physiologic aspects of PBB. PBB is not directly comparable with the more typical flow resistive (R) and dead space (D) loads. According to the terminology of Mead,[12] R is a "passive load" because it is present only during active breathing (ie, flow creates the pressure drop); hence, the subject might effectively modify the load by changing the respiratory pattern (eg, adapting lower flow rates decreases the pressure drop due to R). Conversely, PBB is an "active load" because it is present regardless of the subject's breathing.

The studies of Wilson et al,[10,13] Raven et al,[9] Louhevaara et al,[14] and Arborelius et al[8] carefully evaluate pressure-demand respirators. The analyses focus on the peak pressures and effect on ventilatory work. However, the unique nature of the PBB load (perhaps by changing the pressure-volume relationship of the lung or the

length and efficiency of the ventilatory muscles) warrants consideration of the effect at the resting portions of the respiratory cycle.

The relationship between physiologic and subjective effects of such respirators has been studied. Wilson et al[13] found a poor correlation between breathing sensation and ventilation (expressed as dyspnea index). This suggests that mechanisms other than ventilation (eg, resting lung volume changes) may be relevant. Raven et al[9] also suggested that pressure swings are sensed. This is particularly important because PBB-induced changes in lung volume, respiratory muscle length-tension relationships, or muscle spindle activity[18] may adversely modify the manner in which pressure is sensed.

In summary, PBB, as would occur with use of a positive pressure (pressure-demand) respirator, has significant physiologic impact. Furthermore, the subjective impact is equivalent to that of an ID load. Unlike earlier studies of pressure-demand respirators, this study specifically examined the unique effects of PBB, which differ from resistance loads. The authors postulate that the primary mechanism of this effect is through a change in the FRC. Because of these effects, respirators that use the positive pressure mode should be carefully designed and maintained to provide a stable level of end expiratory pressure rather than allowing it to rise considerably higher than would be necessary to protect against leaks in the sealing surfaces. Furthermore, because of the significance of these effects, workers using positive pressure respirators should be carefully evaluated medically. In unusual, borderline situations, clinicians may wish to empirically test a worker by placing a commercially available PEEP valve in the expiratory limb of a breathing circuit and observing the physiologic and subjective response. There is considerable need for future research into the physiologic effects of PBB to validate the hypothesis that lung volume changes are the mediator of many of the effects and to determine an optimal level of positive pressure. Although only a relatively small proportion of respirator users employ PBB, they do so under particularly adverse and hazardous situations.

Acknowledgments

The authors thank Wendy Binder for preparing this manuscript and Ron Kanter for invaluable assistance with data collection.

Supported by grant RO1-OH-02005 from the National Institute for Occupational Safety and Health.

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