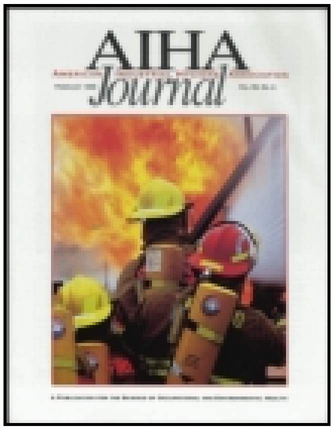

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Alterations in Physiological and Perceptual Variables during Exhaustive Endurance Work while Wearing a Pressure-Demand Respirator*†

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The purpose of this investigation was to describe the time course of changes in physiological and perceptual variables during exhaustive endurance work with and without an air-supplied, full-facepiece, pressure-demand respirator. Thirty-eight healthy subjects (24 to 51 years of age) volunteered for this study. Treadmill speed was set at 5.5 kph (3.4 mph) and elevation was set at a level calculated to elicit 70% of a previously determined maximal aerobic capacity ($\dot{V}O_{2max}$). Subjects continued at this rate to exhaustion. Despite a constant work rate, $\dot{V}O_2$ and $\%\dot{V}O_{2max}$ increased during exercise and were significantly greater with the respirator (34.4 ± 1.1 mL/kg · min; 84% $\dot{V}O_{2max}$) than without the respirator (31.9 ± 1.1 mL/kg · min; 76% $\dot{V}O_{2max}$) at the "final" measurement point prior to termination of exercise by each subject. The final values for ventilation volume ($\dot{V}_E$) also were significantly greater with the respirator (89.2 ± 3.4 L/min) than without (73.4 ± 3.7 L/min). At the conclusion of the endurance walk, dyspnea index ($\dot{V}_E/MMV_{.25}$) remained well below maximal values (with = 58.6 ± 2%; without = 44.6 ± 2%; $p < 0.001$). Also, at the final period, no significant differences occurred in the subjects' perceptual ratings of work of breathing, yet work performance time was significantly reduced ($p < 0.0001$) from 69.1 ± 4.4 min (without) to 55.6 ± 3.8 min (with). A significantly greater swing in peak pressure (maximum pressure measured within the facepiece of respirator), however, from inspired (PP_i) to expired (PP_e) occurred with the respirator (13.42 cmH_2O) than without the respirator (9.25 cmH_2O). The equivalent work intensities of both endurance walks to exhaustion were noted in similar final physiological values for heart rate (HR), frequency of breathing (f_B), and ratings of perceived exertion (RPE) and breathing (BrSc). At 30 min when an equal number of subjects (n = 32) were performing work, RPE and BrSc were increased significantly during respirator wear. This increased perception of work and breathing occurred despite equivalent work loads. Perceptual measures reliably indicated impending fatigue. Therefore, the interaction of added respiratory work over time caused added physiological work that was perceived by the subject and resulted in an earlier termination of work.

Introduction

This investigation into the effects of an air-line supplied, full-facepiece, pressure demand respirator on exhaustive endurance work is the third part of a larger study designed to describe pulmonary function responses[1] and maximal exercise responses[2] to respirator wear.

The majority of studies investigating physiological responses to respirator wear or an increased resistance to breathing during exercise have examined responses during progressive exercise to maximal levels or submaximal exercise for periods of 5 to 30 min.[1-6] Many of these investigations have examined the physiological effects of various types of protective respirator masks, *i.e.*, air purifying, air-supplied, or self-contained breathing apparatus,[1-7] and increased resistances to inspiration and exhalation.[6,7] With the exception of the study by Deno et al.,[8] the maximum length of exercise has been 30 min.[6] There are, however, instances of industrial usage where respirator wear exceeds this time frame. Therefore, it becomes imperative to examine the effects of respirator wear on the physiological and perceptual responses during prolonged work (>30 min).

Deno et al.[8] systematically investigated the physiological effect of increased respiratory resistance to breathing and exercise intensity during prolonged work (*i.e.*, 1 hr) at 35% to 60% of maximum aerobic capacity ($\%\dot{V}O_{2max}$) (See Appendix for a list of abbreviations used in this manuscript). From these data, the authors suggested that a threshold of inspiratory resistance of 8 cmH_2O at 60 L/min was needed before a physiological effect was observed. The investigations failed to discern psychological effects of the increased resistance to breathing, however, and by design did not evaluate perceptual signals associated with pressure swings across the mouth or the interaction of imposed resistance and perception of breathing. As the wearing of a full-facepiece respirator during work has resulted in documented adverse psychological responses,[9] the physiological and perceptual problems associated with long-term wear of a respirator need to be considered. Despite the lack of compelling information concerning long-duration work using respiratory protective equipment, Louhevaara et al.[5] have suggested that continuous use of these devices be limited to less than 30 min. In order to more clearly define the problems associated with long-term work and respirator wear, this investigation was designed to describe physiological and perceptual effects of respirator wear.

*This article is the third in a series of three. Parts One and Two were published in the January and February issues of the Journal.

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Experimental Materials and Methods

One-half of the subject group were fire fighters experienced in respirator wear (n = 19) while the other half were inexperienced (n = 19). These subjects comprise the same subject population used in the two previous investigations.[1,2]

In the present investigation, both physiological and perceptual responses to respirator wear were evaluated during endurance walks to exhaustion. Each subject was scheduled for two exhaustive submaximal exercise tests on two separate days at least one week apart. The exercise tests were performed wearing a pressure-demand, air-supplied respirator, with a full-face mask (MSA-Ultravue Mine Safety Appliances Co., Pittsburgh, Pa.) and without a respirator but using a mouthpiece and noseclip to enable collection of respiratory and metabolic data. The order of respirator testing was randomized for each subject. To simulate actual working conditions, the respirator was worn during the entire endurance test, while the mouthpiece and noseclip were used only during times of data collection. Thus, the endurance test using mouthpiece and noseclip was used as a control test for each subject for comparison to the endurance task with a respirator. Both submaximal exercise tests were performed at a constant speed of 91.12 m/min (3.4 mph). The elevation of the treadmill was set at a level calculated to elicit 70% of the subject's maximal aerobic capacity (70% $\dot{V}O_{2max}$). Treadmill elevations ranged from 2.5% to 18% grade (Figure 1). After an initial warm-up, the first 5 min of the endurance walk was used to confirm that the intensity of the work load was 70% $\dot{V}O_{2max}$. Once correct elevation was determined, this grade was maintained during the entire test and during the subsequent exhaustive endurance test.

The methods for evaluating physiological changes with exercise while wearing a respirator, *e.g.*, flows, pressures, ventilation, and oxygen uptake have been noted previously.[2] It was anticipated, however, that subjects would continue a minimum of 30 min at the submaximal level of 70% $\dot{V}O_{2max}$. Thus, the schedule of data collection was abbreviated as follows: during the first 5 min of each endurance test both with and without the respirator, metabolic, ventilatory, cardiovascular, and perceptual assessments were made and averaged over 30-sec intervals. Similar data were collected for 2 min at 10-min intervals throughout the remainder of the test, as long as the subjects were able to continue, up to a maximum of 120 min.

Subjects were asked to inform testers when they felt they could continue for only 5 more minutes. Breath by breath metabolic and respiratory data were collected on each subject during the final 5 min prior to exhaustion. While subjects were encouraged to continue exercising as long as possible, subjective and objective evaluations of impending exhaustion were based on the subject's ratings of perceived exertion (RPE), increases in heart rate (HR) to maximum or near maximum, increases in ventilation volume ($\dot{V}_E$) and oxygen uptake ($\dot{V}O_2$). The subject's subjective opinion as to impending exhaustion was not always accurate. Thus, if at the end of the designated final 5-min collection the subject could continue, he/she was allowed to continue as long as possible with the continued collection of metabolic and respiratory data on a breath by breath basis until exhaustion. Following the test, a 5-min recovery period was performed during which time subjects walked at 0% grade and 4.8 kph (3 mph). During recovery the subjects continued to wear the respirator, or mouthpiece, and respiratory data were recorded.

The perceptual scales used in this investigation included the Borg scale of perceived exertion (RPE) and a seven-point psychological and category scale designed to measure breathing distress (BrSc). Both of these scales and their use have been described previously.[9] These assessments were made by asking each subject to point at the number which best described his/her perception of the effort and breathing distress at selected points during the exercise bout. Blood pressure and heart rate were measured during each of the data collection periods. The pressure-flow relationship of the respirator was measured against known flows prior to and following the investigation, and remained essentially the same 18 months after the initial measurement, with no significant changes in resistance.

The static pressure measured in the facepiece of the pressure-demand respirator used for exercise was less than 38 mmH_2O with a supply line pressure of 95 psi.[10] Inhalation resistance was less than 32 mmH_2O at 120 L/min, and exhalation resistance was less than 70 mmH_2O at 85 L/min. These values were within federal guidelines for pressure demand apparatus.[10]

All subjects performed both endurance tests to exhaustion, with and without the respirator. The data were analyzed using paired t-tests comparing variables collected with and without the respirator mask during clinical pulmonary function and long-term exercise. Regression analysis was performed using the difference in scores between selected pulmonary and exercise variables from the endurance tests.

Results

Demographic[1] and physiological data at maximal exercise[2] have been presented. Table I, however, contains some

TABLE I
Descriptive Demographic and Physiological Data of Subjects[A]

		$\bar{x}$	P	Range
		80.7 (2.5)		53.8–121.3
$MVV_{.25}$[B]	w/o[C]	168.6 (6.4)	0.001	83.1–256.7
(L/min BTPS)	w[D]	156.2 (6.1)		62.5–238.7
HR_{max}[E]	w/o	185 (2)	0.447	150–201
(beats/min)	w	184 (2)		142–200
$\dot{V}O_{2max}$[F]	w/o	42.2 (1.4)	0.001	24.9–60.6
(mL/kg·min)	w	44.1 (1.3)		29.0–61.0

[A]Means (± standard error of the means).
[B]$MVV_{.25}$ = maximum voluntary ventilation in 15 sec.
[C]w/o = without the respirator.
[D]w = with the respirator.
[E]HR_{max} = maximum heart rate.
[F]$\dot{V}O_{2max}$ = maximal oxygen uptake.

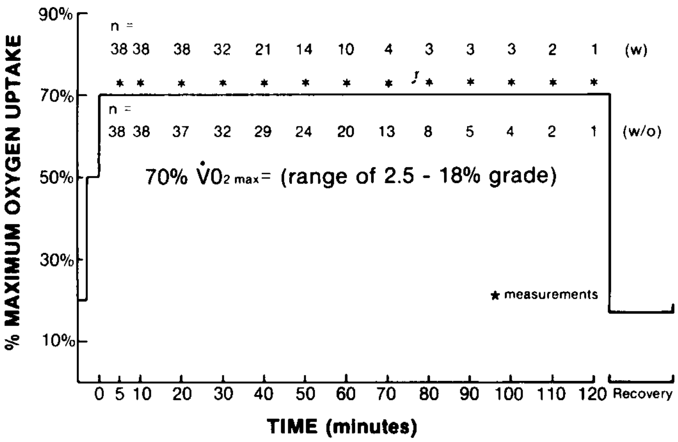

Figure 1—Schematic outline of protocol for endurance test to exhaustion: (number of subjects), w (with), w/o (without). Subjects were allowed to warm up at 5.5 kph (3.5 mph) (20% to 50% $\dot{V}O_{2max}$). At 0 time the incline of the treadmill was raised to the level calculated to elicit 70% $\dot{V}O_{2max}$.

pertinent information for reference as the results of the endurance tests are presented. The increased resistances of the respirator resulted in a significantly ($p < 0.001$) lower average $MVV_{.25}$ with the respirator ($\bar{x}$ = 156.2 ± 6.1 L/min BTPS; ranging from 62.5 L/min to 238.7 L/min BTPS) than without ($\bar{x}$ = 168.6 ± 6.4 L/min BTPS; ranging from 83.1 L/min to 256.7 L/min BTPS). A significant decrease of 13.5 min ($p < 0.02$) in the average work performance time also occurred when wearing the respirator and ranged from a maximum decrease of 72 min (with to without) to an actual increase of 16 min. The correlation coefficients (r) between the difference in scores in $MVV_{.25}$ with and without the respirator and the individual differences in performance time with and without the respirator were not significant ($p = 0.278$).

The changes in mean data during the course of the endurance walk to exhaustion are illustrated in Figures 2-6. The number of subjects completing each 10-min period (Figure 1) indicates subject dropout. While the occurrence of subject dropout is a significant finding in itself, 95% confidence intervals were constructed around the mean data (Figures 2-6) to aid interpretation of physiological response. The 95% confidence interval should illustrate the range of values that can challenge the current respiratory protective devices within 95% of the work force. For clarity, only one-half of the 95% confidence interval (Figures 2-6) has been constructed for each mean. For Figures 2, 3, 5, and 6, the lower half of the confidence level has been used for the mean data without the respirator and the upper half of the 95% confidence interval has been used for the mean data with the respirator. In Figure 4, the lower half of the 95% level has been used for the mean data with the respirator and the upper half of the 95% confidence level has been used for the mean data without the respirator. Data collected at the conclusion of each endurance walk to exhaustion are presented in Table II. A final 5-min collection of data was obtained on each subject regardless of the performance time. As a result, the final value represents the data point at which their own estimation of exhaustion compelled each subject to terminate the exercise. A comparison of final values for oxygen uptake indicated that the $\dot{V}O_2$ and $\%\dot{V}O_{2max}$ at the conclusion of the endurance walk were greater with the respirator than without the respirator ($p < 0.05$).

The average values for minute ventilation ($\dot{V}_E$) with and without the respirator are illustrated in Figure 2. These data, along with the 95% confidence intervals, identify a greater range of $\dot{V}_E$ values with the respirator, particularly during the second hour of work. During the first 60 min, $\dot{V}_E$ at each measurement point was significantly greater with the respirator than without. The lack of significant differences during the second 60 min was probably masked by subject dropout and increased variability. The $\dot{V}_E$ for the final value with the respirator was significantly greater ($p < 0.001$) by almost 16 L/min (Table II). As the breathing frequency (f_B) was not statistically different between the two resistance conditions ($p = 0.177$), the significantly greater mean V_T (with = 2.06 ± 0.07; without = 1.75 ± 0.08) with the respirator was responsible for the greater $\dot{V}_E$ at the final measurement.

Similar to the average $\dot{V}_E$ values, average peak inspired flows (PF_I) were significantly greater with the respirator than without the respirator during the first 60 min of exercise (Figure 3). From 90 min to 120 min of exercise, there was very little difference between average PF_I values with and without the respirator. While the number of subjects reaching this 90-min mark and beyond was small, several subjects reached the 90-min point in both exercise walks. This suggests that those subjects able to work for extended periods (> 90 min) were able to modify their breathing such that the increased inspired resistances of the respirator appeared to have no affect on their PF_I. The mean PF_I value at 60 min of exercise with the respirator was significantly greater than mean PF_I without the respirator, while the levels of $\%\dot{V}O_{2max}$ did not differ significantly between the two endurance walks (with = 75.4 ± 14.0 $\%\dot{V}O_{2max}$; without 70.0 ± 13.4 $\%\dot{V}O_{2max}$).

The ranges of peak expiratory flows (PF_E), decreased somewhat at 60 min of exercise (with = 132.1 to 234.2 L/min; without = 113.1 to 264.0 L/min), while the mean PF_E values were similar (with, $\bar{x}$ = 185.3 ± 36.0 L/min; without, $\bar{x}$ = 178.6 ± 42.0 L/min). The mean PF_E data, with and without the

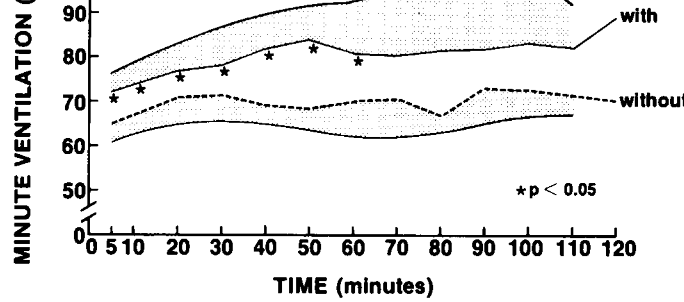

Figure 2—Mean minute ventilation values for endurance exercise tests to exhaustion. Mean $\dot{V}_E$ without (---) and mean $\dot{V}_E$ with (—) the respirator are labeled *without* and *with*.

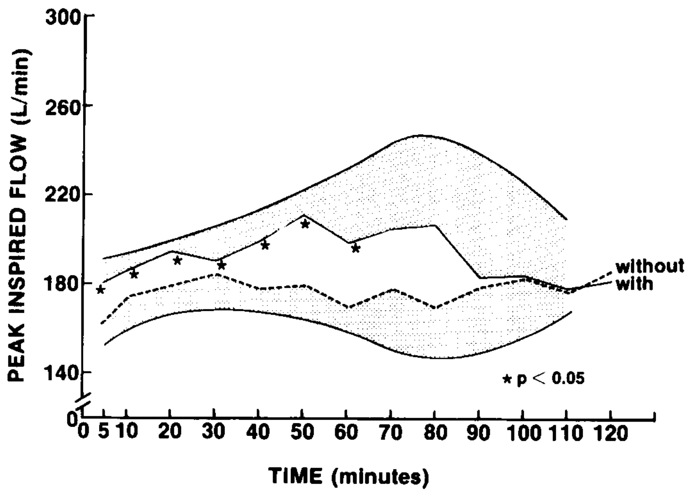

Figure 3—Mean peak inspired flow values for endurance exercise tests to exhaustion. Mean PF_I without (---) and mean PF_I with (—) the respirator are labeled *without* and *with*.

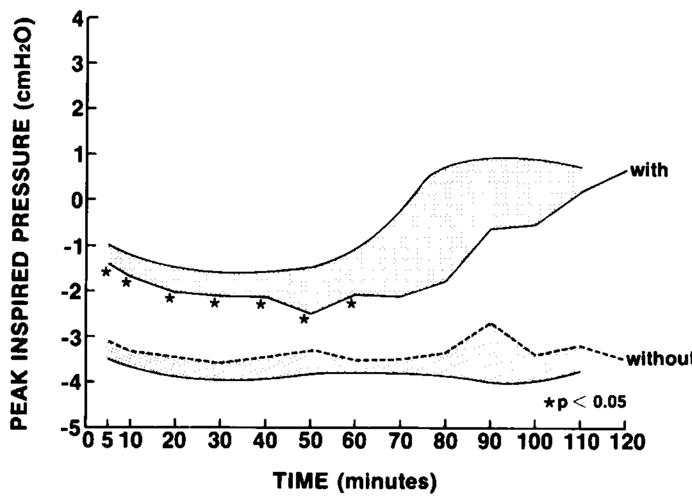

Figure 5—Mean peak inspired pressure values for endurance exercise tests to exhaustion. Mean PF_I without (---) and mean PF_I with (—) the respirator are labeled *without* and *with*.

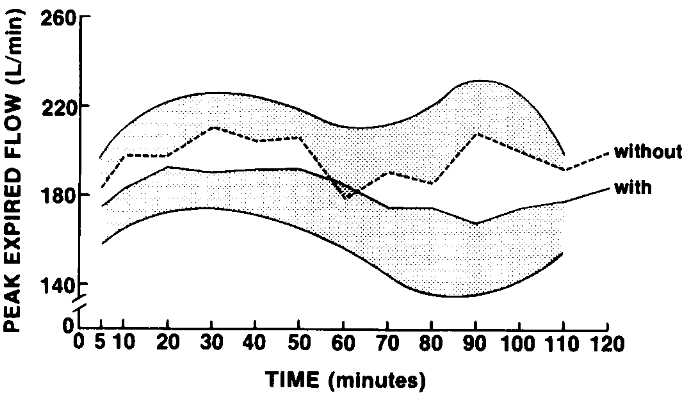

Figure 4—Mean peak expired flow values for endurance exercise tests to exhaustion. Mean PF_E without (---) and mean PF_E with (—) the respirator are labeled *without* and *with*.

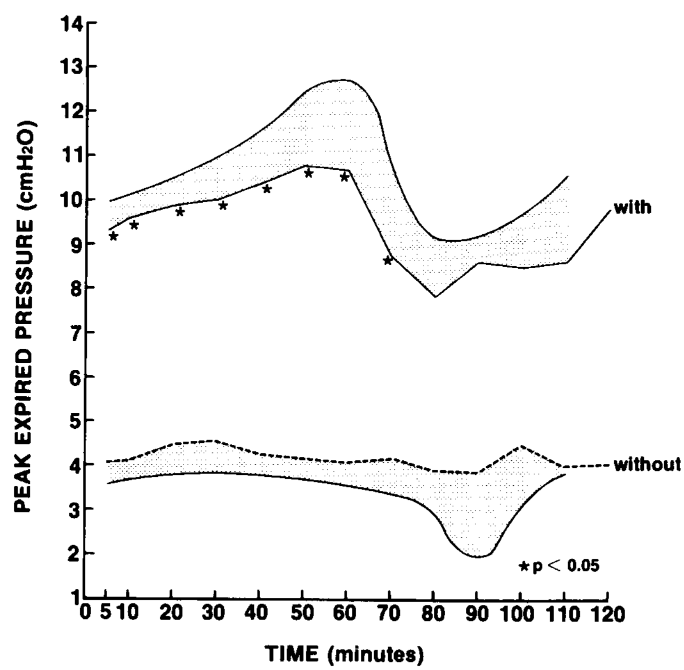

Figure 6—Mean peak expired pressure values for endurance exercise tests to exhaustion. Mean PP_e with (—) and mean PP_e without (---) the respirator are labeled *with* and *without*.

respirator, at each measurement point are illustrated in Figure 4. The extreme variability in the mean data and the large ranges of PF_E values for both endurance walks prevented any significant differences. Average final peak inspired flows were significantly greater while wearing the respirator (with = 211.4 ± 7.5 L/min, without = 190.9 ± 7.8 L/min), yet average peak expired flows were significantly greater without the respirator (with = 202.2 ± 9.6 L/min, without = 212.9 ± 9.3 L/min).

Although the pressure-demand respirator was mechanically equipped to maintain a positive facepiece pressure at 120 L/min flow, peak inspired pressure with the respirator was drawn negative (-1.5 cmH_2O) by 5 min of exercise, thus indicating a loss of positive pressure during inspiration (Figure 5). The average final value for inspired pressure with the respirator was negative (-3.04 ± 0.35 cmH_2O) relative to the atmosphere and ranged from a -7.28 cmH_2O to -0.11 cmH_2O. The inspired peak pressure without the respirator at the final measurement period was -3.99 cmH_2O and ranged from -6.38 cmH_2O to -1.86 cmH_2O. Average peak inspired pressure with the respirator, however, began to move toward decreasing negative pressure, becoming positive at 110 min through 120 min. Again, it appears that those subjects continuing for the longest periods of time are able to adapt their respiratory requirements to the limitations of the respirator.

The peak expired pressures with the respirator were more than twice the level of the peak expired pressure values without the respirator (Figure 6). The peak expired pressures with the respirator were at least 7 cmH_2O up to 12 cmH_2O, while five subjects had expired pressures from 12 cmH_2O to 20 cmH_2O. In contrast, the peak expired pressure values without the respirator ranged from only 2 cmH_2O to 6 cmH_2O with only two subjects at peak expired pressures from 8 cmH_2O to 11 cmH_2O. Data at the termination of the endurance walk (Table II) indicated that peak expired pressures with the respirator were almost two times the peak expired pressures without the respirator and yet generated similar expired flows in both conditions.

The average dyspnea index (a calculated ratio of $\dot{V}_E/MVV_{.25}$) at final measurement period (58.6 ± 2.1%) was significantly greater while wearing the respirator than when not using the respirator (without = 44.6 ± 2.0%). During the final period of data collection, heart rate (HR), breathing scale, and ratings of perceived exertion were not significantly different between exercise with or without the respirator. Since these category scales have a ceiling, however, and since the subjects presumably were at maximum in both conditions, the ratings should not have differed. Despite there being no significant differences between the two protocols in terms of workload, the time at which these equivalent responses were measured averaged 13.5 min earlier in the walk with the respirator than without the respirator.

The data in Table III illustrate the time course of changes in selected ventilatory measures with and without the respirator. These data are the means at 30, 60, 90, and 120 min. The significantly greater $\dot{V}_E$ was caused by an increased V_T as the f_B values were not significantly different with or without the respirator during the first 60 min of exercise. The change in the combination of f_B and V_T with the respirator represents an attempt by the subjects to attain the most efficient means of ensuring adequate oxygen uptake. With the exception of the average measures at 30 min of exercise, V_T with the respirator was always greater than without. The greater V_T was the primary factor in the significantly greater $\dot{V}_E$ also occurring at the final measurement (Table II).

The heart rate data presented in Table III indicate that there were no significant differences in average HR between the two resistance conditions despite the 13 bpm and 30 bpm differences at 90 min and 120 min, respectively. The subject who completed 120 min of exercise with the respirator was not the same subject who completed 120 min of exercise without the respirator. The work loads were kept constant for all subjects across both test conditions. Therefore, it was not surprising that there were no significant differences in HR between the two endurance walks.

The breathing scale was used to quantify respiratory distress by asking subjects to rate their breathing (BrSc) on a seven-point scale.[9] The ratings at 5 and 30 min of exercise (Table III), when subject number was equal, were significantly greater with the respirator than without. In addition, perceived exertion with the respirator was significantly greater than without the respirator at 30 min of exercise. From 30 to 60 min of exercise, more than 20 subjects had terminated their exercise test with the respirator, while only 12 subjects ended their exercise test without the respirator. With an equal number of subjects continuing the endurance walk through 30 min, one-half hour of exercise appears to be representative of the time in which to expect a heterogenous population to continue work with a respirator. Despite the two tests being carried out at equivalent work loads, however, the subjects perceived the work as greater with the respirator than without, $P < 0.05$.

TABLE II
Physiological and Perceptual Data at Termination of the Exhaustive Endurance Walk (Last Time Values)[A]

Variable	With Respirator	Without Respirator	P Value
Performance time (min)	55.6 (3.8)	69.1 (4.4)	0.015
$\dot{V}O_2$[B] (mL/kg·min)	34.4 (1.1)	31.9 (1.1)	0.001
% $\dot{V}O_{2max}$[C]	84.0 (2.0)	76.0 (1.0)	0.001
HR[D] (beats/min)	177 (3)	178 (3)	0.535
$\dot{V}_E$[E] (L/min BTPS)	89.2 (3.4)	73.4 (3.7)	0.001
V_T[F] (L)	2.06 (0.7)	1.75 (0.08)	0.003
f_B[G] (number/min)	39 (1)	37 (1)	0.177
Inspired flow (L/min)	211.4 (7.5)	190.9 (7.8)	0.001
Expired flow (L/min)	202.2 (9.6)	212.9 (9.3)	0.195
Inspired pressure (cmH_2O)	-3.04 (0.35)	-3.99 (0.18)	0.001
Expired pressure (cmH_2O)	+10.38 (0.45)	+5.26 (0.31)	0.001
D.I.[H] ($\dot{V}_{Emax}/MVV_{.25}$)	58.6 (2.1)	44.6 (2.0)	0.001
Breathing distress	4.4 (0.2)	4.0 (0.2)	0.085
Perceived exertion	17.2 (0.4)	17.2 (0.4)	0.998

[A]Means (± standard error of the mean).
[B]$\dot{V}O_2$ = oxygen uptake.
[C]% $\dot{V}O_{2max}$ = percent of maximal oxygen uptake.
[D]HR = heart rate.
[E]$\dot{V}_E$ = ventilation volume.
[F]V_T = tidal volume.
[G]f_B = breathing frequency.
[H]D.I. = dyspnea index.

Discussion

The data of the present investigation clearly demonstrate the interaction of the person-respirator interface on the ability to perform prolonged work, and they confirm previous reports by Deno et al.[8] and Louhevaara.[7] An evaluation of the physiological and perceptual data with and without the respirator at the final values (Table II) indicated no significant differences in heart rate, frequency of breathing, rate of perceived exertion, and breathing scale. The endurance exercise tests were carried out under equivalent environmental conditions and work rates. The average work performance time of the 38 subjects, however, was reduced 13.5 min with the respirator and ranged from a +16 min (*i.e.*, a +41% individual increase) to a maximum decrement of -72 min (*i.e.*, a -63% individual decrease). The ventilatory load during this final measurement period, as indicated by minute ventilation, peak expired pressure, ventilatory equivalent for 1 L of oxygen ($\dot{V}_E/\dot{V}O_2$), and the calculated dyspnea index ($\dot{V}_E/MVV_{.25}$), was greater during respirator wear and was reflected by an increase in $\dot{V}O_2$ for the same work rate. Åstrand[11] has identified a 70% dyspnea index as being related to maximal work capacity, yet, in comparison, the dyspnea index values in the present study were much lower. Subjects did reach a significantly higher dyspnea index, and at a significantly earlier time frame, while exercising with the

TABLE III
Time Course of Changes in Ventilatory Measures with and Without the Respirator[A]

Time (min)	5		30		60		90		120	
	With	Without	With	Without	With	Without	With	Without	With	Without
	38	38	32	32	10	20	3	5	1	1
Tidal volume	2.47[B]	2.11	2.17	2.10	2.30	1.98	2.48	2.00	2.53	1.56
	(.08)	(.07)	(.08)	(.09)	(.15)	(.09)	(.04)	(.12)		
Breathing frequency	28	26	33	31	32	30	29	38	26	44
(breaths/min)	(1)	(1)	(1)	(1)	(2)	(2)	(2)	(3)		
Heart rate	154	150	168	169	173	171	158	171	150	180
(beats/min)	(3)	(3)	(3)	(3)	(4)	(3)	(10)	(6)		
Breathing scale	2.8[B]	2.2	3.6[B]	2.7	3.4	3.1	3.3	3.5	3	4
	(.2)	(.1)	(.2)	(.2)	(.3)	(.3)	(.3)	(.7)		
Ratings of perceived exertion	12.3	12.0	14.9[B]	13.6	15.5	14.8	14.3	14.8	16	15
	(.2)	(.3)	(.3)	(.4)	(.8)	(.6)	(.7)	(1.4)		

[A]Means (± standard error of the mean)
[B]$p < 0.05$

respirator, thus indicating utilization of a significantly higher proportion of their pulmonary reserve capacity.

The design features of the pressure-demand type respirator are such that a significantly greater protection is generated by reason of maintaining positive pressures within the facepiece. Thus, the negative pressures within the facepiece of the respirator that occurred throughout the endurance walk to exhaustion (Figure 5) are cause for concern. The concern arises primarily from the potential loss of protection caused by inward leakage of contaminants when positive pressure within the facepiece is compromised. The increased protection factor of the pressure demand respirator has been demonstrated adequately at rest and during light work.[12] Raven et al.[3] reported peak inspired flows ranging from 40 L/min to 200 L/min at 80% $\dot{V}O_{2max}$, resulting in peak negative inspired pressures of -9 to -10 cmH_2O similar to those found in a demand respirator system. It also was found, however, that ventilatory demands at 35% $\dot{V}O_{2max}$ were producing negative inspired pressures.[3] Consequently, the expectation of increased protection as a result of positive pressure breathing was valid only at rest. The results, along with the findings of the present study, indicate that a significantly increased potential for inward leakage of contaminants can occur at work loads as low as 35% $\dot{V}O_{2max}$. Obviously, further work on protection factors during heavy work loads needs to be carried out with the intent to redesign the positive pressure respirator.

The work of breathing is usually such a small fraction of the total energy turnover of normal individuals that it is considered of minor importance. Very high ventilations, however, such as found in high intensity work or the addition of external resistive loads, may require significant increases in respiratory work. Many individuals who work at high intensity levels, *e.g.*, fire fighters, wear self-contained breathing apparatus (SCBA). The effects of the additional weight (16 kg, 35 lb) on physiological responses to work at or near maximal levels for extended periods of time must be considered also. In a study by Myhre et al.[13] the additional weight of an SCBA pack raised $\dot{V}O_2$ values 240 mL/min at 50% $\dot{V}O_{2max}$ and 475 mL/min at 80% $\dot{V}O_{2max}$. This represents an added energy cost from 17% to 20%. The added work imposed by the SCBA produced a significantly greater ventilatory requirement which ranged from +18% for the 50% $\dot{V}O_{2max}$ work load to +43% for the 80% $\dot{V}O_{2max}$ work load. In the present study, the average final % $\dot{V}O_{2max}$ was 84% with a $\dot{V}_E$ of 89.2 L/min. A 43% increase in $\dot{V}_E$ would result in a $\dot{V}_E$ of 127.6 L/min, well within the range of maximal levels of minute ventilation.[11] A legitimate concern at $\dot{V}_E$ levels measured at relatively light work rates is whether or not the user really can depend upon a 30-min air supply from a standard 30-min cylinder. The service time for an SCBA is determined by a breathing machine requiring 40 L/min and by the respiratory requirements of the wearer walking on a level treadmill at 4.8 kph (3 mph, Reference 10). At a work intensity resulting in a $\dot{V}_E$ of 89.2 L/min, a 30-min air supply would last 13.5 min and only 9.4 min at a $\dot{V}_E$ of 127.6 L/min.

The ventilatory equivalent for oxygen ($\dot{V}_E/\dot{V}O_2$) was significantly greater at the final measurement period with the respirator. The increase in $\dot{V}_E/\dot{V}O_2$ can be attributed to an increase in ventilation caused by lactic acid accumulation. The final work intensity, however, was significantly greater with the respirator than without ($p < 0.001$; Table II). Thus, the increase in $\dot{V}_E/\dot{V}O_2$ with the respirator may be caused by an "excess ventilation" over and above the hyperventilation normally seen when anaerobic threshold is passed. The question remains as to why $\dot{V}_E$ and $\dot{V}O_2$ increased significantly with respirator wear at equivalent physical work loads. Was the increase in $\dot{V}O_2$ with the exercise time with the respirator caused by the increased $\dot{V}_E$ as a result of excess ventilation? Or was it caused by a greater metabolic drive because of an increased work of breathing to overcome the resistances of the respirator, or a combination of both?

The increased ventilatory response seen during respirator wear was indicative of a mismatch between the muscular force generated and the stimulus to breathe. Dempsey et al.[14] discussed the concept of a "descending neural stimulus for hyperpnea," developed almost a century ago by Krogh and Lindhard,[15] and pointed out that central neural mechanisms that initiate muscular contraction and sustain it might also mediate the accompanying excess ventilation by increasing the spread of neural activity: *i.e.,* the harder a given muscle mass works, the greater the neural discharge to it, and consequently, the greater the neural discharge to the ventilatory muscles. Thus, this explanation attempts to link the force of the ventilatory drive to the force of muscular contraction and metabolic rate by linking neural pathways. A major factor to consider in the use of the respirator is the resistance that it offers to breathing. Extra mechanical work, in the form of increased respiratory muscle activity, must be done to overcome the increased resistance to breathing. The functional pathways for the control of hyperpnea, as indicated by Dempsey et al.[14] receive feedback or error detection from several sources, including feedback from the lung and airway receptors to the central nervous system. The feedback from the chest wall and lungs would be concerned with mechanical events, such as flow-pressure and volume-tension relationships. Apparently, $\dot{V}_E$ was optimized during the endurance test in the respirator by increasing V_T and decreasing f_B over the course of the test (Table III). Therefore, increased respiratory load must have altered afferent traffic to the medullary respiratory centers, producing changes in the neural control of breathing.

Admittedly, the theory that increased respiratory load comprises a primary feed forward stimulus to increase ventilation in humans is tentative; however, hyperventilation as a distress response has been documented previously with the use of industrial respirators.[16] It is not clear as to whether or not the disturbed respiratory patterns should be viewed as a stimulus, a response, or a mediating variable in the distress process.[9] It has been reported that approximately 90% of any given sample of test subjects are able to judge accurately the physiological cost of work.[16] Previous studies[1,2,9] have demonstrated that perception of breathing is significantly increased in subjects performing moderate to heavy work while wearing a respirator. Consequently, in the present study, the significantly greater perception of breathing with the respirator at 5 and 30 min of exercise was expected (Table III). It also is known that $\dot{V}_E$ is influenced in part by psychogenic factors[17] and a central drive.[14] The tactile cues provided by wearing of a full-facepiece respirator contributed, no doubt, to the significant increase in $\dot{V}_E$ and $\dot{V}_E/\dot{V}O_2$.

In summary, the authors conclude that respirator wear during endurance exercise to exhaustion results in a significant increase in the physiological effort of breathing to overcome the added resistances. The increased effort of breathing increases the perception of exercise intensity and results in an earlier termination of exercise, by an average of 13.5 min. The continued increase in PP_e over the first 30 min appears indicative of an excessive ventilation response, which is confirmed by the significantly greater $\dot{V}_E/\dot{V}O_2$. Those individuals who continued for a significantly shorter period of time (30 min) with the respirator were experiencing respiratory and psychological distress as evidenced by the sharp increase in RPE and BrSc. Thus, the authors agree with Louhevaara et al.[7] that, given the current respirator designs, continuous use of these devices should be limited to a maximum of 30 min.

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APPENDIX

Abbreviations Used

BrSc—perception of breathing

BTPS—body temperature and pressure saturated

DI—dyspnea index

f_B—frequency of breathing

F_EO_2—fraction of expired oxygen

HR—heart rate

$MVV_{.25}$—maximum voluntary ventilation in 15 sec

PF_E—peak expired flow

PF_I—peak inspired flow

PP_e—peak expired pressure

PP_i—peak inspired pressure

RPE—ratings of perceived exertion

$\dot{V}_E$—ventilation volume

$\dot{V}_{Emax}$—maximal ventilation volume

$\dot{V}O_2$—oxygen uptake

$\dot{V}O_{2max}$—maximal oxygen uptake

V_T—tidal volume

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