

Effects of Industrial Respirators on Breathing Pattern, Gas
Exchange, and Heart Rate During Exercise

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Abstract

The effects of a filtering device and an air-line apparatus on breathing pattern, gas exchange, and heart rate were studied in nine construction workers with a low and in nine firemen with a high physical work capacity. The control values without the respirators were measured twice with a low-resistance breathing valve. In the analysis the subjects' mean absolute dynamic work load was equal with the breathing valve. The respirators did not alter breathing pattern. For the construction workers the mean ventilation volume with the breathing valve and the respirators (23.73 l/min) was significantly greater than for the firemen (21.30 l/min). With the filtering device the firemen's oxygen consumption (1.08 l/min) was significantly higher than the control values (0.89-0.95 l/min) and the values obtained with the air-line apparatus (0.96 and 0.97 l/min). When the subjects wore the respirators, their respiratory exchange ratio (0.75-0.84) was consistently lower than the control values (0.85-0.97). The use of the filtering device and the air-line apparatus changed the subjects' cardiorespiratory responses primarily by increasing their oxygen consumption and decreasing their respiratory exchange ratio. When studied during submaximal aerobic exercise, the alterations were not influenced by low physical work capacity.

Introduction

Industrial respirators are required at work when technical and organizational controls prove insufficient to prevent health hazards caused by exposure to contaminated atmospheres. In industry respirators are worn only during 20-30 % of the work phases evaluated as needing respiratory protection (Aucoin, 1975; Vihma, 1981). Failure to use a respirator is generally attributed to their additional burden on respiratory organs.

However, studies with filtering (air-purifying) devices (Hermansen et al., 1972; Steinhaus et al., 1984) and air-line (supplied-air) apparatus (Arborelius et al., 1983; Dahlbäck and Balldin, 1984) have shown that, during light or moderate work typical of industrial tasks with respirators (Louhevaara et al., 1985), pulmonary ventilation and gas exchange differs only slightly from values obtained without the respirators. The subjects of these investigations were young and usually in good physical condition. Therefore, their high physical work capacity may have concealed the undesirable effects of the respirators on the variables studied.

Because no studies with a filtering device and an air-line apparatus have been carried out using subjects with both low and high physical work capacity, it has been difficult to evaluate the effects of low physical work capacity on the physiological responses to respirator use.

Consequently, the aim of the present study was to determine the effects of a filtering device and an air-line apparatus on breathing pattern, gas exchange, and heart rate in healthy men with either low or high physical work capacity. In the analysis the subjects' mean absolute dynamic work load was equal without the respirators.

Material and methods

Subjects

The voluntary subjects comprised 18 healthy men, nine construction workers aged 35-44 years and nine firemen aged 21-35 years. The construction workers' mean maximal oxygen consumption ($\dot{V}O_{2\max}$) was 34.5 ml/min $\cdot$ kg, and that of the firemen was 66.9 ml/min $\cdot$ kg (Table 1). The construction workers' physical work capacity was classified as low and the firemen's as high. The subjects regularly wore a respirator at work. Four of the construction workers and two of the firemen were smokers.

Table 1. Subjects' physical characteristics. The maximal values are based on the results of a maximal exercise test with the breathing valve.

Variable	Construction workers (N=9)		Firemen (N=9)	
	Mean	Range	Mean	Range
Age, years	41.0	35.0-44.0	26.0	21.0-35.0
Height, cm	175.0	168.5-183.0	175.0	167.0-186.0
Weight, kg	84.0	71.5-97.0	70.5	60.0-80.5
Maximal oxygen consumption, ml/min $\cdot$ kg	34.5	27.6-40.6	66.9	58.7-82.3
Maximal oxygen consumption, l/min	2.89	2.40-3.67	4.70	3.76-5.82
Maximal pulmonary ventilation, l/min	88.3	68.8-125.2	125.6	111.2-141.0

Procedures

After a medical screening that included a clinical stress test, the subjects' $\dot{V}O_{2\max}$ was determined directly on a treadmill (Louhevaara et al., 1984). A few days after the maximal exercise test, the men performed a submaximal experiment on a treadmill on two different occasions separated by a minimum interval of one day. Both experiments consisted of the following two test series: (i) a control test with a breathing valve and a test with a filtering device and (ii) a control test with a breathing valve and a test with an air-line apparatus. The tests within the two series and the test series themselves were performed in random order. Every test contained the same five phases, each of which lasted 5 min. The first phase consisted of sitting at rest; the next three involved walking at (i) light (22-29 % of relative aerobic strain, i.e., $\% \dot{V}O_{2\max}$), (ii) moderate (40-47 $\% \dot{V}O_{2\max}$), and (iii) heavy (59-60 $\% \dot{V}O_{2\max}$) exercise levels; and the last was a recovery period during which the subjects once again sat. The treadmill grades and speeds that corresponded with the target exercise levels of 20, 40, and 60 $\% \dot{V}O_{2\max}$ were determined individually for each subject according to the results of the individual's maximal exercise test. In the control tests the breathing valve was only worn during the last 2 min of each test phase. The filtering device and the

air-line apparatus were used continuously during the whole test period of 25 min. The control tests were separated from the tests with a respirator by a rest period of at least 30 min. During all the tests the ambient temperature was 21-25°C, and the relative humidity 30-50 %. The subjects wore shorts and sneakers.

Equipment and measurements

A Collins modified Douglas breathing valve (Collins, USA) with a mouthpiece and a noseclip was used for the maximal exercise test and both control tests. The filtering device included a conventional half-face mask with combined dust and gas filters (Kemira Silner 12, Kemira, Finland). The air-line apparatus was a compressed supplied-air breathing apparatus of the pressure-demand type with a full-face mask and a nosepiece (Aga Air-line, Aga, Sweden). The external dead space of the breathing valve was 60 ml. The corresponding values of the filtering device and air-line apparatus were 195 and 225 ml, respectively. The flow-pressure characteristics of the equipment used are presented in Fig. 1. The arrangements used to measure dead space and flow-pressure characteristics have been reported previously by Louhevaara et al. (1984).

An elastic hose, through which expired air was collected, was attached with a plastic joint glued to the outlet of

the filtering device and the air-line apparatus. The length of the hose was 150 cm (diameter 4 cm). An HP 21072B pneumotachograph (Hewlett-Packard, USA) connected to an HP 4739⁰4 respiratory transducer (Hewlett-Packard, USA) was placed at the end of the hose for measuring the flow rate of the expired air. The air flow rate was calibrated against a Godart flow calibration set (Godart-Statham, Holland). The flow rate was recorded with a Scintag chart recorder (Scintag, Switzerland).

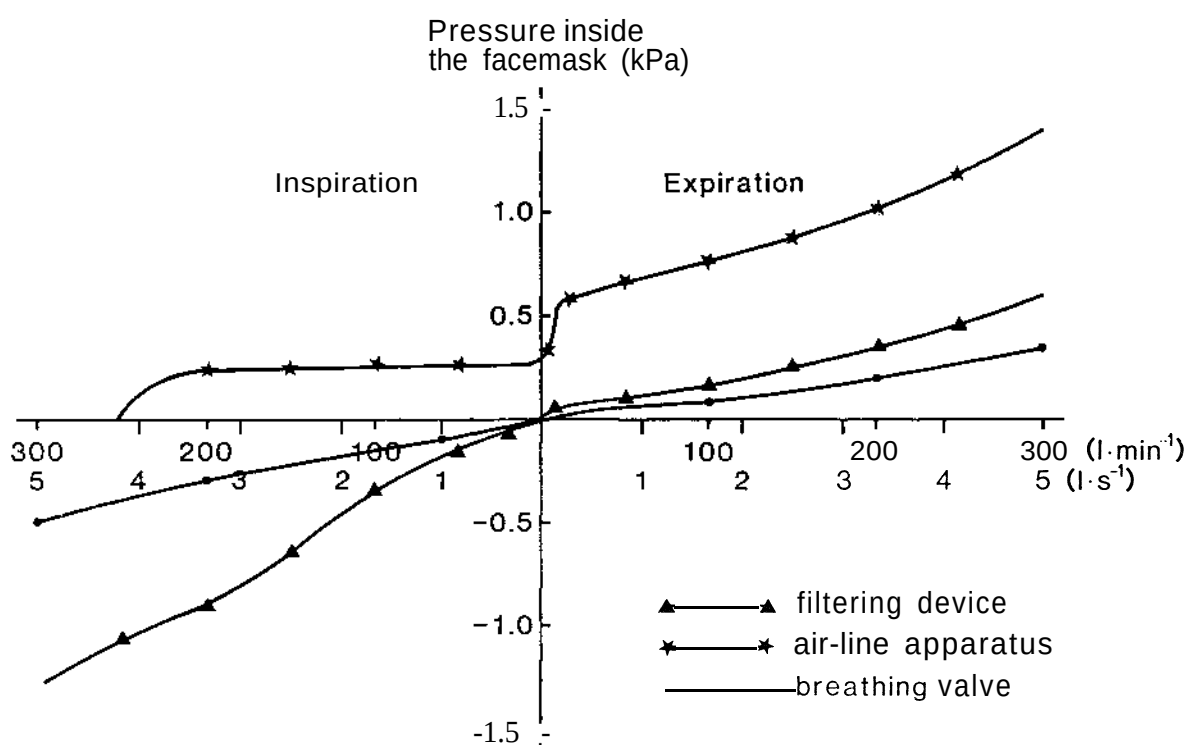


Figure 1. Flow-pressure characteristics of the filtering device, the air-line apparatus, and the breathing valve used in the tests.

Inspiratory time, expiratory time, and breathing frequency for the last minute of each 5-min test phase were calculated from the recordings of the air flow rate. The calculations were made with a Hipad TM digitizer (Houston Instrument, USA) connected to an ABC 80 microcomputer (Metric, Sweden). Breathing pattern was analyzed according to the concept introduced by Milic-Emili and Grunstein (1976) that pulmonary ventilation ($\dot{V}$) is the product of mean inspiratory flow (V_I/T_I , l/s) and inspiratory duty cycle (T_I/T_{tot} , dimensionless) according to the equation:

$$\dot{V} = 60 \cdot (V_I/T_I) \cdot (T_I/T_{tot}).$$

In the equation mean inspiratory flow reflects the "drive" component and inspiratory duty cycle the "timing" component of ventilation.

During the last minute of each test phase the amount of expired air was measured with an HP 3308A integrator (Hewlett-Packard, USA) or the ABC 80 microcomputer. For the gas analysis a continuous sample of expired air (150 ml/min) was led from the hose to analyzers 20 cm before the pneumotachograph. The expired air was analyzed for oxygen with a polarographic gas analyzer (Beckman OM 14, Beckman, USA) and for carbon dioxide with an infrared gas analyzer (Datex CD 101, Datex, Finland) . The analyzers were

calibrated with standard gas mixtures before every test. Oxygen consumption and the production of carbon dioxide were calculated with the ABC 80 microcomputer according to standard formulas.

During the tests an electrocardiogram (ECG) was monitored continuously and recorded during each test minute with a Mingograf 34 (Siemens-Elema, FRG). Heart rate per minute was calculated according to 16 successive QRS-complexes.

The average heart rate of the last 2 min of each test phase corresponded to the heart rate at work.

Statistics

The two-way analysis of variance with repeated measurements and the Student's t-test for group means were employed in the analysis of the effects of the respirators and physical work capacity on the variables studied.

The group variables were (i) type of breathing equipment (four levels: filtering device, breathing valve-control 1, air-line apparatus, and breathing valve-control 2) and (ii) the subjects' occupation, which defined their physical work capacity (two levels: construction workers with low physical work capacity and firemen with high physical work

capacity). If the overall F ($p(F) < 0.05$) due to type of breathing equipment or occupation was significant for a dependent variable, the significance of the differences between the cross-tabled means was tested with the t -test.

The statistical analysis was carried out with the mean results of four of the five test phases performed by the subjects. The mean absolute oxygen consumption (dynamic work load) of the four phases was equal for the construction workers (0.91 and 0.95 l/min) and the firemen (0.91 and 0.89 l/min) according to the control values measured twice with the breathing valve (see Table 3). The phases selected for analysis for the construction workers were sitting at rest, walking at moderate ($47\ \% \dot{V}O_{2\max}$) and heavy ($60\ \% \dot{V}O_{2\max}$) exercise levels, and sitting for recovery. The corresponding phases for the firemen were sitting at rest, walking at light ($22\ \% \dot{V}O_{2\max}$) and moderate ($40\ \% \dot{V}O_{2\max}$) exercise levels, and sitting for recovery.

Results

The analysis of variance revealed a statistically significant overall F between ventilation volume and occupation ($p(F) < 0.001$). Between the group variables and

mean inspiratory flow (V_T/T_I) and inspiratory duty cycle (T_I/T_{tot}) the F-values were not significant. A significant F was determined between oxygen consumption and type of breathing equipment ($p(F) < 0.05$) and between respiratory exchange ratio and type of breathing equipment ($p(F) < 0.001$) and occupation ($p(F) < 0.05$). The F-values calculated for the production of carbon dioxide and the group variables were not significant. The analysis between heart rate and occupation produced a significant F-value ($p(F) < 0.001$).

The t-tests showed that the ventilation volume of the construction workers with the breathing valve (24.48 & 23.22 l/min) and with the air-line apparatus (23.87 l/min) was significantly greater than the corresponding values of the firemen (20.62 & 21.32 l/min and 21.37 l/min, respectively) (Table 2).

The oxygen consumption of the firemen was significantly higher with the filtering device (1.08 l/min) than with the breathing valve (0.89-0.95 l/min) and the air-line apparatus (0.96 and 0.97 l/min) (Table 3).

Table 2. Pulmonary ventilation (l/min) of the construction workers and firemen during the use of different types of breathing equipment.

Type of equipment	<u>Construction workers</u>		<u>Firemen</u>		p(T) -value due to occupation
	Mean	SD	Mean	SD	
Filtering device	23.33	3.54	21.92	3.40	NS
Breathing valve-control 1	24.48	3.90	20.62	4.24	< 0.001
Air-line apparatus	23.87	3.44	21.37	3.77	< 0.01
Breathing valve-control 2	23.22	4.06	21.32	3.37	< 0.05

Table 3. Oxygen consumption (l/min) of the construction workers and firemen during the use of different types of breathing equipment.

Type of equipment	<u>Construction workers</u>		<u>Firemen</u>		p(T) -value due to occupation
	Mean	SD	Mean	SD	
Filtering device	0.93	0.14	1.08 ^a	0.17	< 0.001
Breathing valve-control 1	0.91	0.13	0.91	0.19	NS
Air-line apparatus	0.97	0.23	0.96	0.16	NS
Breathing valve-control 2	0.95	0.20	0.89	0.17	NS

^a p(T) < 0.001, vs. the firemen's two control values and their value for the air-line apparatus.

Table 4. Respiratory exchange ratio of the construction workers and firemen during the use of different types of breathing equipment.

Type of equipment	Construction workers		Firemen		p(T) -value due to occupation
	Mean	SD	Mean	SD	
Filtering device	0.84 ^a	0.06	0.78 ^b	0.06	< 0.001
Breathing valve-control 1	0.92	0.08	0.93	0.11	NS
Air-line apparatus	0.75 ^c	0.11	0.79 ^b	0.08	NS
Breathing valve-control 2	0.85	0.08	0.97	0.11	< 0.001

^a p(T) < 0.001, vs. the construction worker's control value 1 and their value for the air-line apparatus.

^b p(T) < 0.001, vs. the firemen's two control values.

^c p(T) < 0.001, vs. the construction workers' two control values.

Table 5. Heart rate (beats/min) of the construction workers and firemen during the use of different types of breathing equipment.

Type of equipment	Construction workers		Firemen		p(T) -value due to occupation
	Mean	SD	Mean	SD	
Filtering device	103	11	97	11	< 0.05
Breathing valve-control 1	100	11	92	8	< 0.01
Air-line apparatus	106	15	95	11	< 0.01
Breathing valve-control 2	103	15	94	10	< 0.01

When the subjects wore the filtering device or the air-line apparatus their respiratory exchange ratios ranged from 0.75 to 0.84 and were consistently lower than the control values measured with the breathing valve (0.85-0.97) (Table 4).

With the breathing valve and the respirators the construction workers had heart rates ranging from 100 to 106 beats/min. These values were significantly higher, with the mean increase of 10 %, than those of the firemen (92-97 beats/min) (Table 5).

Discussion

Work load

In the present study the test phases were selected for analysis so that the mean absolute oxygen consumption, i.e., dynamic work load, of a group of subjects with a low physical work capacity (the construction workers) would be equal to that of a group with a high physical work capacity (the firemen). The standardization of the work loads was based on control values measured twice with the breathing valve. During the tests the construction workers had a mean oxygen consumption of 0.93 l/min ($32 \text{ \%}\dot{V}O_{2\max}$), and the firemen a corresponding value of 0.90 l/min ($19 \text{ \%}\dot{V}O_{2\max}$).

The subjects' oxygen consumption with the breathing valve varied from 0.29 to 1.87 l/min, and the range of $\dot{V}O_{2\max}$ was 10-60 and 7-40 for the construction workers and firemen, respectively.

In a field study (Louhevaara et al., 1985), with jobs that required the regular use of different respirators, the mean oxygen consumption ranged from 0.5 to 1.7 l/min (12-62 $\dot{V}O_{2\max}$) for work with a filtering device and from 0.7 to 1.1 l/min (21-50 $\dot{V}O_{2\max}$) for work with an air-line apparatus. The highest $\dot{V}O_{2\max}$ levels were determined for subjects whose physical work capacity was low. Thus the dynamic work load of our present study corresponded well to actual work load in tasks with a filtering device or an air-line apparatus.

During the construction workers' heaviest exercise phase of 60 $\dot{V}O_{2\max}$, their tidal volume was 40 % of their forced vital capacity. Their ventilatory responses were under the exercise hyperventilation point of about 50 % of forced vital capacity, when tidal volume levels off and breathing frequency begins to rise more steeply (Hey et al., 1966; Folinsbee et al., 1983). The exercise hyperventilation point is usually near the anaerobic threshold (Wasserman et al., 1973). Before this point the ventilation volume/oxygen

consumption ratio is almost constant, and after it the ratio increases.

Our comparisons were made during submaximal exercise that was below the anaerobic threshold for both the construction workers and the firemen. This design was selected for the statistical evaluation of the data because one aim of the study was to determine whether a subject's low physical work capacity accentuates the effects of either a filtering device or an air-line apparatus on cardiorespiratory responses during exercise. In addition, we were able to combine the results of the different test phases because the effects of the respirators did not vary at different exercise levels (Louhevaara, unpublished results).

Breathing pattern

Neither the filtering device nor the air-line apparatus induced changes in the subjects' ventilation volume, mean inspiratory flow, or inspiratory duty cycle.

In previous studies with filtering devices and air-line apparatus, breathing pattern has been analyzed with respect to ventilation volume and its main components, breathing frequency and tidal volume. Hermansen et al. (1972)

reported that during submaximal exercise a filtering device (gas mask) reduced ventilation volume by lowering breathing frequency although the tidal volume tended to increase in comparison to reference values measured with a low-resistance breathing valve. When a lowered breathing frequency caused by the use of a filtering device was compensated for by an increased tidal volume, the ventilation volume remained the same as the reference values or was slightly increased (Steinhaus et al., 1984). The present and previous results suggest that it is primarily the magnitude of the additional breathing resistance of a filtering device, higher during inspiration and in inverse relation to the protective efficiency of the device, that affects breathing pattern.

The results we obtained with the air-line apparatus agree with the findings by Arborelius et al. (1983) for submaximal exercise. They reported that an air-line apparatus caused a slight increase in breathing frequency that tended to increase ventilation volume when compared with reference values.

The construction workers of our study had, on the average, a ventilation volume that was 11 % larger than the firemen's (23.73 vs. 21.30 l/min) with the breathing valve

and the respirators. The increased ventilation volume was primarily the result of the construction workers' shorter mean expiratory time (2.0 vs. 2.4 s) and higher mean breathing frequency (17.8 vs. 16.0 breaths/min). These differences did not reflect the subjects' mean inspiratory flow or inspiratory duty cycle, i.e., the "drive" and "timing" components of pulmonary ventilation. No differences were detected in the inspiratory time or tidal volume of the two groups. These observations agree with the results of Folinsbee et al. (1983) who found that the breathing frequency, and also expiratory time of highly-conditioned athletes and their sedentary counterparts varied according to the subjects' $\dot{V}O_{2\max}$ during exercise.

Physical training increases $\dot{V}O_{2\max}$ and may also produce a specific breathing pattern. In firefighting drills firemen are instructed to breathe slowly and deeply, and this training may have affected the results of our study. The firemen were also, on the average, 15 years younger than the construction workers, and the difference in age may also have had some influence on breathing pattern.

Unfortunately, the design of our study did not allow the separate effects of $\dot{V}O_{2\max}$, age, and training on breathing pattern to be determined.

Gas exchange and heart rate

When the firemen wore the filtering device their oxygen consumption was unexpectedly high during exercise. This occurrence may be explained by the additional inspiratory and expiratory breathing resistance of the filtering device (Fig. 1), accompanied by the firemen's specific breathing pattern. The dead spaces of the respirators were almost equal (195 and 225 ml). With the filtering device the firemen were able to maintain and even increase their ventilation volume with a low breathing frequency primarily by using a prolonged expiration time and retaining their tidal volume at the same level as with the breathing valve. The construction workers' breathing frequency tended to increase, and their tidal volumes were slightly but consistently decreased by the filtering device. The firemen's breathing pattern, with its unchanged tidal volume and long expiratory time, increased the work of breathing and affected oxygen consumption.

The lowered values of the respiratory exchange ratio during the use of the respirators suggest that the respirators disturbed gas exchange, and the disturbance resulted in the retention of carbon dioxide.

The respirators did not affect the subjects' heart rate. The construction workers had, on the average, a 10 % higher

heart rate during exercise than the firemen. Working heart rate greatly depends on an individual's $\dot{V}O_2$ max at work. In our comparisons it was 13 % higher for the construction workers than for the firemen.

With the exclusion of the firemen's high oxygen consumption with the filtering device, the gas exchange and heart rate measured during the use of the respirators were similar to corresponding values reported in earlier studies with filtering devices (Hermansen et al., 1972; Lerman et al., 1983; Steinhaus et al., 1984) and air-line apparatus (Raven et al., 1982; Arborelius et al., 1983; Dahlbäck and Balldin, 1984). According to the earlier results oxygen consumption, the production of carbon dioxide, and heart rate remain almost unchanged with the use of the respirators during submaximal exercise. Some observations with filtering devices showed that they induce hypoventilation and the retention of carbon dioxide and increase heart rate at heavier submaximal exercise levels (Hermansen et al., 1972; Lerman et al., 1983).

In our study the alterations in breathing pattern, gas exchange, and heart rate during the use of a filtering device and an air-line apparatus were minor, and, when studied during submaximal aerobic exercise, they were not influenced by a subject's low physical work capacity.

References

- Arborelius, M., G.O., Dahlbäck, and P-G. Data (1983),
"Cardiac output and gas exchange during heavy exercise
with a positive pressure respiratory protective
apparatus," Scand. J. Work Environ, Health 9:471-477.
- Aucoin, T.A. Jr. (1975), "A succesful respirator program,"
Am. Ind. Hyg. Assoc. J. 36:752-754.
- Dahlback, G.O., and U.I. Balldin (1984), "Physiological
effects of pressure demand masks during heavy
exercise," Am. Ind. Hyg. Assoc. J. 45:177-181.
- Folinsbee, L.I., E.S., Wallace, J.F., Bedi, and S.M.
Horvath (1983), "Exercise respiratory breathing pattern
in elite cyclist and sedentary subjects," Med. Sci.
Sports 15:503-509.
- Hermansen, L., Z., Vokac, and P. Lereim (1972),
"Respiratory and circulatory response to added air flow
resistance during exercise," Ergonomics 15:15-24.

Hey, E.N., B.B., Lloyd, D.J.C., Cunningham, M.G.M., Jukes, and D.P.G. Bolton (1966), "Effects of various respiratory stimuli on the depth and frequency on breathing in man," Respir. Physiol. 1:193-205.

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

Louhevaara, v., T., Tuomi, O., Korhonen, and J.Jaakkola (1984), "Cardiorespiratory effects of respiratory protective devices during exercise in well-trained men," Eur. J. Appl. Physiol. Occup. Physiol. 52:340-345.

Louhevaara, V., T., Tuomi, J., Smolander, O., Korhonen, A., Tossavainen, and J. Jaakkola (1985), "Cardiorespiratory strain in jobs that require respiratory protection," Int. Arch. Qccup. Environ. Health 55:195-206.

Milic-Emili, J., and M.M. Grunstein (1976), "Drive and timing components of ventilation," Chest 70 (Suppl.):131-133.

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

Steinhaus von, I., T.H., Hettinger, and G. Eissing (1984), "Belastung und Beanspruchung durch das Tragen von Atemschutzgeräten," Arbeitsmed. Sozialmed. Präventivmed. 19:24-29.

Vihma, T. (1981), "Health hazards and stress factors in small industry - Prevalence study in the province of Uusimaa with special reference to the type of industry and the occupational title as classification for the description of occupational health problems," Scand. J. Work Environ. Health 7:1-149.

Wasserman, K., B.J., Whipp, S.N., Koyal, and W.L. Beaver (1973), "Anaerobic threshold and respiratory gas exchange during exercise," J. Appl. Physiol 35:236-243.