Scand J Work Environ Health 1984;10(5):275-281

<https://doi.org/10.5271/sjweh.2327>

Issue date: Oct 1984

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This article in PubMed: www.ncbi.nlm.nih.gov/pubmed/6395324

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Physiological effects associated with the use of respiratory protective devices

A review

by Veikko A Louhevaara, LSc¹

LOUHEVAARA VA. Physiological effects associated with the use of respiratory protective devices: A review. *Scand J Work Environ Health* 10 (1984) 275–281. Several types of filtering (air-purifying) devices, air-line (supplied-air) apparatus, and self-contained breathing apparatus are used at work. The most important parameters of the respiratory protective devices that affect physical work capacity are additional inspiratory and expiratory breathing resistance, dead space, and weight. The main physiological effects of the respirators are alterations in breathing pattern, hypoventilation, retention of carbon dioxide, and increase in the work of breathing. The undesirable effects are accentuated during heavy physical work, maximal physical work capacity thereby being reduced.

Key terms: breathing pattern, gas exchange, heart rate.

Attempts to prevent health hazards caused by exposure to contaminated atmospheres usually focus on the technical and organizational arrangements of the work involved. The use of respiratory protective devices, or respirators, is required when other preventive controls prove insufficient. Respirators are usually classified into the following three major categories according to their technical factors and efficiency: (i) filtering (air-purifying) devices, (ii) air-line (supplied-air) apparatus, and (iii) self-contained breathing apparatus (50). The first type may be mounted with different dust and/or gas filters. The latter two are atmosphere-supplying respirators. They can be either demand or pressure-demand (continuous safety pressure inside the face mask) in type. Respirators are generally used with a full-face or a half-face mask.

Above all else respirators must be efficient. And their efficiency is highly dependent on the amount and manner of use.

Research results have indicated that respirators are available and in use in only 20–30 % of the work phases evaluated as needing them (3, 63). Failure to use a respirator is influenced by psychological factors (44, 45, 46), by the additional burden on the respiratory organs, and by thermal stress (51).

The most important parameters affecting physical work performance with a respirator include the additional inspiratory and/or expiratory breathing resistance involved, the external dead space of the

equipment, and the weight of the apparatus. These parameters are presented for different types of respirators in table 1. The values are based on recent measurements with new equipment.

In industry filtering devices and air-line apparatus are usually worn in light or moderately heavy tasks of a long duration (41). The use of a self-contained breathing apparatus is limited to short durations in rescue and repair tasks which often require maximal or near maximal physical effort (32, 35, 43, 65).

More scientific information about respirators is needed for both their proper use and technical design. The aim of the present review is to highlight the effects of different factors associated with the use of respirators on breathing pattern, respiratory gas exchange, and heart rate in man. The effects reviewed have been studied during submaximal and maximal work at normal ambient temperature and pressure. The physiological aspects of the use of respirators have previously been reviewed in 1976 by James (25) and in 1979 by Raven et al (50). The main results obtained before 1960 have been published by Cooper (9) and Silverman et al (56).

Additional breathing resistance

Inspiratory breathing resistance

In the studies reviewed the inspiratory breathing resistances added varied from 0.4 to 5.1 kPa at air-flow rates of 1.0–2.0 l/s. The subjects were usually male, rather young, and well-trained (15, 17, 18). However, in one investigation (42) they were coal miners over the age of 45 years, and in another two of the nine subjects were women (21).

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Table 1. Breathing resistance, dead space, and weight of different types of respirators.

Respirator	Breathing resistance ^a at an airflow rate of 1.4 l/s		Dead space ^c (ml)	Weight (kg)	Reference
	Inspiratory ^b (kPa)	Expiratory ^b (kPa)			
Filtering device, half- or full-face mask	0.3—0.5	0.2—0.3	195—500	0.5—1.0	Stemler & Craig (59), Louhevaara et al (40)
Air-line apparatus, demand type, full-face mask	0.3—0.8	0.2—0.3	350—790	1.0	Raven et al (52), Arborelius et al (1)
Air-line apparatus, pressure-demand type, full-face mask	^d	0.4—0.7	225—826	1.0	Raven et al (49), Arborelius et al (1), Louhevaara et al (40), Dahlback & Balldin (12)
Self-contained breathing apparatus, pressure-demand type, full-face mask	^d	0.6	90	15.0	Louhevaara et al (40)

^a The normal airway resistance of man is 0.05—0.2 kPa at an airflow rate of 1.0 l/s (10).

^b 1 kPa = 102 mm H₂O = 7.50 mm Hg (torr) = 10 mbar.

^c The anatomic dead space of man is about 150 ml (10).

^d Positive safety pressure: 0.3—0.8 kPa up to the airflow rates of 2.5—5.0 l/s.

During submaximal exercise added inspiratory breathing resistance decreased breathing frequency, prolonging the inspiratory time of young subjects (17, 18, 21). The subjects' tidal volume remained almost unchanged. The breathing frequency of older subjects was unchanged, but their tidal volume decreased (42). When the breathing frequency or tidal volume was reduced, ventilation rates began to decrease, particularly at heavier exercise levels, in comparison to reference values measured with a conventional low-resistance breathing valve (15, 17, 18). Oxygen consumption and the production of carbon dioxide remained the same or increased slightly in young subjects, whereas both decreased in older subjects (17, 18, 42). Heart rate tended to increase with higher inspiratory breathing resistances (15, 21). Dressendorfer et al (15) found no effect on the anaerobic threshold, which was determined on the basis of the respiratory variables.

At near maximal or maximal exercise levels (over 80 % of maximal oxygen consumption) under added inspiratory breathing resistance, the ventilation rate remained 30—45 % and oxygen consumption 10—15 % lower than the reference values (15). There were also slight decreases in the production of carbon dioxide, the respiratory exchange ratio, and heart rate.

Dressendorfer et al (15) removed the added inspiratory breathing resistance shortly before the subjects became exhausted. The ventilation rate immediately rose to a level equaling the reference value measured at maximal exercise without the added breathing resistance, and oxygen consumption rose to a level higher than its reference value. The subjects were also able to continue the exercise for at least 1 min.

From the preceding information it can be stated that inspiratory breathing resistance added during submaximal and, particularly, maximal exercise hinders ventilation and results in hypoventilation and

the retention of carbon dioxide. The different breathing patterns of subjects, coupled with considerable interindividual differences, produces unpredictable changes in gas exchange at light and moderate exercise levels.

Expiratory breathing resistance

At submaximal and near maximal exercise levels the primary effect of added expiratory breathing resistance (0.5 kPa at an airflow rate of 2.0 l/s) was to decrease tidal volume, which led to a decrease in the ventilation rate and to hypoventilation (18).

In the studies of Tabakin & Hanson (61) and Levy et al (37) added expiratory breathing resistance (0.5 kPa at an airflow rate of 0.7 l/s) produced abrupt decreases in the ventilation rate, oxygen consumption, and the production of carbon dioxide of normal male subjects during steady-state submaximal exercise. However, they found that oxygen consumption returned to the reference level or to a slightly higher level after about 2 min. The ventilation rate remained constantly lower, however, and it took several minutes for the production of carbon dioxide to return to its reference level. Once the added breathing resistance was removed, the respiratory variables rebounded to levels above their reference values.

Significant changes in cardiac output occurred with added expiratory breathing resistance, but the changes observed were unpredictable with regard to magnitude, direction, and time of occurrence (20). Furthermore, added expiratory breathing resistance has been found to alter lung volume and to impair the uniform distribution of gas in the lungs (62).

Inspiratory and expiratory breathing resistance

In some studies (8, 13, 14, 18) both the inspiratory and expiratory breathing resistances were increased

by 0.5—5.6 kPa at airflow rates of 1.4—2.0 l/s. The subjects of these investigations were rather young men, usually in good physical condition.

Gee et al (18), Cerretelli et al (8), and Deno et al (14) found that the ventilation rate consistently decreased during submaximal exercise as the breathing resistances were increased. After a plateauing of tidal volume at higher exercise levels (23, 38) a further increase in breathing frequency, and thus in ventilation rate, was restricted (8, 18). Up to that level the changes in gas exchange and heart rate were rather minor (8, 13, 18). During near maximal or maximal exercise oxygen consumption was reduced to about 20 % and ventilation rates to 30—50 % of the values measured without the added breathing resistances (8, 13, 14). The work of breathing increased among the subjects who attempted to ventilate normally despite the increased resistances. Demedts & Anthonisen (13) observed that strongly ventilating subjects responded also briskly to elevated concentrations of carbon dioxide in inspired air at rest.

Research results so far strongly suggest that added expiratory breathing resistance hampers ventilation more than a corresponding increase in inspiratory resistance (13, 18).

External dead space

The external dead spaces used in studies of this phenomenon have varied from 36 to 1 400 ml (4, 21, 27, 30, 53). The subjects were usually young men.

During submaximal exercise the ventilation rate increased almost linearly as the size of the external dead space increased (4). Small increases in the ventilation rate were attained primarily through increased tidal volume (30). Tidal volume was found to increase to as much as 70 % of the vital capacity (30). When tidal volume increased, the dead space : tidal volume ratio was diminished and had a smaller effect on respiration (53). The ventilation rate was found to increase when the external dead space exceeded 50 ml (4).

External dead space did not have a constant effect on oxygen consumption or on the production of carbon dioxide (4, 27). At heavier exercise levels a higher ventilation rate, combined with the additional work of breathing, tended to increase heart rate (27).

The great interindividual differences observed in the effects of external dead space may partly be explained by the subjects' ventilatory response to carbon dioxide when measured at rest (27), because external dead space stimulates ventilation via the hypercapnoeic drive.

Extra weight

Weight-carrying has been found to increase ventilation rate, oxygen consumption, and heart rate at submaximal exercise levels (6, 40, 54, 58). During

heavier exercise the values for the respiratory variables were not linearly dependent on the extra weight (19, 57). Intervening factors that have been observed to affect the additional strain include the subject's body weight and the biomechanical factors of carrying the weight at various speeds and different grades on a treadmill (19, 40). Extra weight has been found to cause a considerable decrease in maximal physical work capacity (49).

Type of respirator

Filtering devices

The inspiratory and expiratory breathing resistances of the filtering devices used in the reviewed studies varied from 0.2 to 0.9 kPa and from 0.1 to 0.3 kPa, respectively, at an airflow rate of 1.0 l/s (11, 16, 22, 36, 40, 58, 59). The dead space was 100—200 ml (see table 1). The subjects comprised young men in good physical condition.

At submaximal exercise levels the use of a filtering device often lowered the ventilation rate by lowering breathing frequency (22, 58) (table 2). Oxygen consumption and the production of carbon dioxide remained almost unchanged up to an exercise level of 75—80 % of the maximal oxygen consumption when compared to the reference values (22). If the ventilation rate was maintained, oxygen consumption was found to increase, probably because breathing required more work (40). The use of a filtering device induced hypoventilation and the retention of carbon dioxide, particularly at heavier exercise levels (22, 36, 40).

Filtering devices of low efficiency induced very small inspiratory and expiratory breathing resistances (< 0.1 kPa at an airflow rate of 1.0 l/s), and the cardiorespiratory responses were found to be negligible (60, 64). However, external dead space tended to increase the ventilation rate (60, 64). Apparently all the devices used to collect expired air (ie, different valves with a mouthpiece and a noseclip or face masks) change the natural breathing pattern and tend to stimulate ventilation (2, 24, 55).

During maximal exercise with a filtering device a critically short expiratory time (0.66 s), discussed by Johnson & Berlin (26), was attained earlier because the filtering device increased the ratio of inspiratory to expiratory time. The approach of the critically short expiratory time may be related to a subject's decision to stop exercising (11, 59). During maximal exercise the use of a filtering device reduced ventilation by 30—45 % and oxygen consumption by 14—21 % (22, 36). These findings are indicative of severe hypoventilation. The maximal heart rate was found to be unaltered or slightly decreased (16, 22, 36) (table 2). Maximal endurance time was limited considerably when a filtering device was used. Increased peak inspiratory pressure and an increased

Table 2. Effects of a filtering device with a high efficiency, a pressure-demand type of air-line apparatus, and a pressure-demand type of self-contained breathing apparatus on breathing pattern, gas exchange, and heart rate during submaximal and maximal exercise. The differences were obtained in a comparison with reference values measured with a breathing valve. (+ + : strong increase, + : increase, =/+ : no difference or increase, = : no difference, =/- : no difference or decrease, - : decrease, --- : strong decrease)

Variable	Filtering device		Air-line apparatus		Self-contained apparatus	
	Submaximal exercise	Maximal exercise	Submaximal exercise	Maximal exercise	Submaximal exercise	Maximal exercise
Inspiratory time	+	+	=/-	=/-	=/-	+
Expiratory time	=/+	+	=	=	=/-	+
Breathing frequency	-	-	=/+	=/+	=/+	-
Tidal volume	=/+	-	=	-	-	-
Ventilation rate	=/-	---	=/+	=/-	=/+	---
Oxygen consumption	=/+	-	=/+	=	=	-
Carbon dioxide production	=/-	-	=	=/-	=	---
Heart rate	+	=/-	=/+	=/-	++	=

retention of carbon dioxide were also observed. The systolic blood pressure remained unchanged (16, 22, 36).

Air-line apparatus

In recent studies with the demand or pressure-demand type of air-line apparatus (table 1) the subjects were primarily well-trained or normal men (1, 12, 40). However Raven et al (48, 52) used female subjects and also individuals with impaired lung function in their studies.

During submaximal exercise with an air-line apparatus, a slight increase in breathing frequency tended to increase gas exchange and heart rate, particularly at heavier exercise levels (table 2) (1, 40). Arborelius et al (1) found that a demand type of apparatus caused no effects on blood gas tensions and hemodynamic variables during submaximal exercise. With the pressure-demand type of apparatus, they found that stroke volume and cardiac output tended to increase. No significant changes in blood pressure have been observed during and after the use of the air-line apparatus (1, 48, 52).

Raven et al (48, 52) found no differences in the physiological effects of the demand or the pressure-demand type of apparatus on normal and impaired subjects. However, with the latter type of equipment, half of the subjects were unable to finish exercising at the heaviest level (80 % of maximal oxygen consumption) because the pressure swing inside the mask exceeded 2.4 kPa.

During maximal exercise the use of a demand or pressure-demand type of air-line apparatus had no significant effect on endurance time, respiratory gas exchange, and blood lactate (1, 12). With a pressure-demand type of apparatus the maximal heart rate and respiratory exchange ratio tended to be lower than with a low-resistance breathing valve (table 2) (1, 12).

Air-line apparatus have much in common with filtering devices. When either is worn, the interaction of the additional inspiratory and/or expiratory

breathing resistance and external dead space affect physical work performance. The extra weight of the respirators is minor. Both alter breathing pattern primarily in the following two ways, with great inter-individual variability:

1. Breathing frequency decreases, but a corresponding increase in tidal volume may occur. The respiratory phase is extended, and the length of the extension is dependent on the location of the additional breathing resistance.

2. Breathing frequency remains almost unchanged, but tidal volume decreases. The changes in the ratio of inspiratory to expiratory time are minor.

When breathing pattern 1 occurs, the deterioration in the ventilation rate is slight. Oxygen consumption remains unchanged or increases slightly, a phenomenon which may lead to hypoventilation. The production of carbon dioxide tends to decrease and results in a decreased respiratory exchange ratio and an increased retention of carbon dioxide. Both heart rate and the work of breathing increase.

Breathing pattern 2 leads to a decrease in ventilation rate, oxygen consumption, and the production of carbon dioxide. Gas exchange becomes more superficial and deficient. The ventilation rate is decreased in an attempt to avoid the additional breathing work induced by the increased breathing resistances. The decreased ventilation rate evidently leads to the retention of carbon dioxide and hypoxia. The anaerobic energy sources are probably taxed earlier. The changes in heart rate are usually negligible.

When either an air-line apparatus or a filtering device are used for a long period, the changes in the breathing pattern and gas exchange cause uncomfortable sensations at the very least. The user's strain at work increases although the changes in classical work-physiological variables (ie, oxygen consumption and heart rate) may be unnoticeable. This is the case particularly with the new models of air-line apparatus, for which the differences detected for all the

physiological variables studied were very small during submaximal and maximal exercise (1, 12).

Self-contained breathing apparatus

The face mask of a self-contained breathing apparatus is technically similar to the face mask of an air-line apparatus (table 1), but the air-containers of the self-contained breathing apparatus usually weigh 15–16 kg (40, 49, 58). The subjects of the studies included in this section mostly comprised young firemen in good physical condition.

In one study (39) the harness of the heavy self-contained breathing apparatus was consistently found to limit tidal volume at submaximal exercise levels. At higher exercise levels a typical strong increase in breathing frequency was restricted. At progressive steady-state exercise levels both inspiratory and expiratory time was noted to decrease almost linearly. Gas exchange and heart rate increased considerably more than without the apparatus. Severe hypoventilation and the retention of carbon dioxide occurred (table 2).

During maximal exercise with a self-contained breathing apparatus, the observed decreases in ventilation and oxygen consumption were 21–44 % and 10–12 %, respectively (40). The maximal heart rate was not altered (40, 49).

According to experiments in which a self-contained breathing apparatus was used with or without a face mask, the extra weight of the air-containers was found to cause almost all the additional physiological strain measured during submaximal exercise (40, 49, 58). It also accounted for a decreased maximal physical work capacity (49). In addition, the physiological effects of the extra weight were greatly influenced by the way the weight was carried (28).

With a lighter apparatus (self-contained, self-rescuer, 3.4 kg) (47), designed for use in escape maneuvers from underground coal mines (29), the physiological differences detected during submaximal exercise were small in comparison to the reference values. Breathing frequency decreased slightly, and the mouth pressure swing increased.

Good physical and mental work capacity are essential for a person using a self-contained breathing apparatus because the heavy equipment is often worn under very demanding work conditions. However, several studies have shown typical users (ie, firemen) to have an average level of physical fitness that does not differ much from that of a sedentary population (7, 31, 33, 34).

Conclusions

From the studies reviewed in the present communication, the following conclusions can be drawn:

1. The additional breathing resistances and external dead spaces of modern-day respirators are

low. The breathing resistances of respirators increase over time if the equipment is not properly cared for. The extra weight of self-contained breathing apparatus is still a very crucial factor that impairs physical work performance.

2. All types of respirators alter the user's natural breathing pattern and cause at least subjective sensations of discomfort.

3. Although submaximal work with a filtering device or an air-line apparatus causes only slight changes in gas exchange and heart rate, hypoventilation and the retention of carbon dioxide may occur. With a self-contained breathing apparatus increases in gas exchange and heart rate are very apparent.

4. The undesirable effects of respirators become accentuated during heavy physical work that requires a ventilation rate of < 25.0 l/min. At near maximal or maximal work levels the use of a filtering device and a self-contained breathing apparatus, in particular, limits physical work capacity seriously.

5. Accurate recommendations for the use of a filtering device or an air-line apparatus cannot be given because experiments of long duration have not been carried out, and few studies have been done with female subjects or with subjects whose physical work capacity has been lowered by illness or age. However, the continuous use of these types of respirators should be limited to periods as short as possible (< 30 min), and sufficient intervals of rest should be allowed. The use of an air-line apparatus is preferable to a filtering device whenever possible, particularly, if a user's physical work capacity is decreased. Although the physiological effects of the demand or the pressure-demand type of air-line apparatus are almost the same, the use of a pressure-demand type is recommended.

6. The use of a self-contained breathing apparatus in firefighting tasks in which oxygen consumption often exceeds 2.0 l/min can be recommended only for healthy individuals whose maximal oxygen consumption is at the very least 3.0 l/min. During repetitive use it would be preferable to allow the heart rate to return to close its initial level before the self-contained breathing apparatus is used again. As an age-induced decline in maximal oxygen consumption is inevitable, effective physical training is necessary to maintain the good physical work capacity required for the use of a self-contained breathing apparatus.

7. Several authors have emphasized the importance of the individual characteristics of persons wearing respirators (21, 25, 44). Individuals who have pulmonary or cardiovascular disorders or experience excessive additional distress with a respira-

tor should always be examined medically before they are allowed to use respirators. The examination should include stepwise increasing submaximal exercise tests for 20–30 min with and without a respirator on a bicycle ergometer. The heaviest exercise level in the tests should be greater than the actual work load incurred with a respirator. A suitable target level might be 60–80 % of the maximal heart rate estimated for the subject. If psychophysiological responses (eg, heart rate) to respirator use are abnormal or differences are marked between the tests, these individuals should not use respirators.

8. Research results concerning the effects of a respirator on breathing pattern, waveform shape (5), and the anaerobic threshold are few. In addition very limited information is available about the physical demands of industrial jobs that require respiratory protection.

Acknowledgments

The author wishes to acknowledge the valuable advice given by O Korhonen, MD, A Tossavainen, DTech, T Tuomi, MSc, J Smolander, MSc, and J Jaakkola, LSc, during the preparation of this review.

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Received for publication: 20 January 1984