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Work Performance When Breathing Through Very High Exhalation Resistance

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Abstract

Exhaling through the inspiratory filters of an air-purifying respirator mask could potentially increase the capacity of the filter to remove 5-10 times the amount of airborne contaminant compared to a filter with unidirectional flow. To test whether humans can tolerate exhaling through a high resistance, ten subjects were tested walking on a treadmill at a constant work rate designed to elicit 75-80% of their maximum heart rates. They wore no mask, a standard M17 full-facepiece mask, and an M17 mask modified so that both inhalation and exhalation flows went through the filters. Three of the subjects could perform no work while wearing the modified mask, and the remainder could perform only about 25% of the work that they could while wearing the standard mask.

Introduction

Although not reported in the literature, there is a limited amount of data that indicates that the capacity of charcoal filters to remove contaminant vapors from the air can be increased (Figure 1) by periodically reversing the flow through the filters (Boardway, 1973). The reverse flow must consist of pure air, and not contaminated air. The mechanism increasing filter capacity is presumably that as the pure air passes back through the filter it takes with it some of the contaminant molecules that were absorbed on the charcoal.

There are emergency situations where such a filter capacity increase could be used to advantage. The ability for light weight respirator masks to remove airborne contaminants could perhaps be greatly enhanced, and the time available to escape from such incidents as mine disasters could perhaps

be lengthened considerably, if wearers exhaled through the filters (Howe, 1992). There is a strong question, however, whether or not people can perform physical labor when breathing through a high exhalation resistance.

There is very little work reported in the literature to give an answer to this question. Almost all literature reports describe experiments using air-purifying respirator masks with relatively high inhalation resistance and low exhalation resistance. Only in the work by Stemler and Craig (1977), where exercise performance times were found to depend on levels of combined inhalation and exhalation resistances, is there an indication of the penalty paid by breathing through extremely high levels of exhalation resistance.

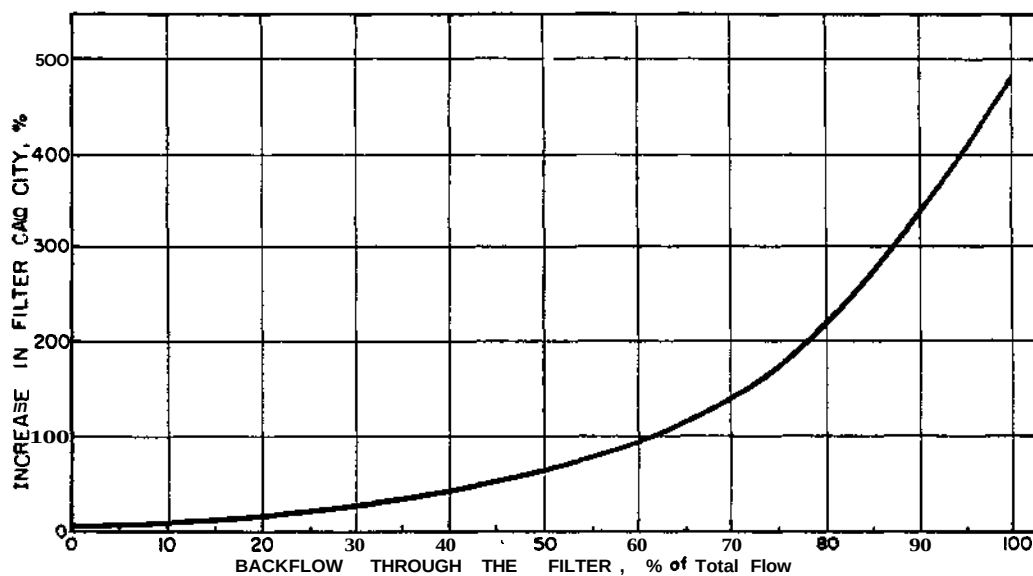


Figure 1. Filter capacity for further contaminant uptake as influenced by the amount of backflow through the filter in alternating flow. The backflow is given as percent of forward flow (Boardway, 1973).

Breathing at rest is usually accompanied by active inhalation and passive exhalation (Johnson, 1991). Actively using chest and abdominal muscles to exhale is an unnatural experience, and must be learned. Breathing during moderate to very heavy physical activity, however, involves active exhalation (Johnson *et al.*, 1992; Johnson, 1993). Thus, high exhalation resistances that are burdensome at rest should not be quite as noticeable during physical work. Wearers of pressure-demand air-supplied self-contained breathing apparatus notice the high effort required to exhale at rest, but the effort is

much less noticeable during work. It is possible, therefore, that people could tolerate extremely high exhalation resistances as long as they were engaged in physical activity high enough that exhalation would normally be active.

It was, therefore, the objective of this experiment to determine how long mask wearers could tolerate working while breathing through an exhalation resistance equal to the inhalation resistance of an air-purifying mask.

Methods

Ten subjects (four female and six male) between the ages of 18 and 34 were recruited for this study from the University of Maryland student population. All subjects were informed of the medical risks and safety precautions involved. Subjects completed health history questionnaires, which were reviewed prior to the study to assure that subjects did not suffer from respiratory, cardiovascular, orthopedic, or other conditions that would affect their abilities to perform exercise testing. No facial hair was permitted, since this would interfere with the mask seal. Subjects were also required to complete a Spielberger State-Trait Anxiety Inventory Test (STAI)

(Spielberger *et al.*, 1970), and highly anxious subjects (STAI scores greater than 45) were eliminated from this study (Johnson *et al.*, 1995).

All subject were familiar with respirator wear from previous testing completed just prior to these tests. No mask and standard mask data were obtained from these previous tests. All subjects were fit with medium facepiece respirators.

Each subject underwent an initial exercise stress test using the Standard Bruce Protocol (ACSM, 1986) to determine maximum heart rate and maximum

oxygen consumption. From these values, individual workload on the treadmill was determined to elicit 75-80% of maximum heart rate for each subject.

A U.S. Army full-facepiece respirator mask (M17) was used in this study. The mask was modified by sealing the exhalation valve and removing inhalation valves to allow backward airflow through the cheek pouch filters. It should be noted that this modification was certain to also increase respirator dead volume because inspiratory and expiratory air flows mixed inside the facepiece.

Subjects were given several modified M17 respirator masks to wear during different test sessions. They were not told in advance which

masks had high exhalation resistance, although the high resistance mask was immediately obvious to them when they wore it.

Heart rate data were monitored continuously from a 3-lead ECG (Model 302 ECG Monitor, Rigel, Morden, Surrey, England).

Subjects continued until their voluntary end points. That is, the subjects continued exercising on the treadmill until they decided to quit. Once they indicated their desire to stop, the treadmill grade was returned to zero and the speed was reduced to a nominally slow speed to allow them to walk gently until their heart rates dropped to 120 bpm or less. Masks were removed immediately post-exercise.

Results

Subject data appear in Table 1. Subjects were young, fit (as indicated by maximum oxygen uptakes), and not anxious (STAI score less than about 35).

Test results are found in Table 2. Three subjects became wary of the high resistance mask, and either

would not, or could not, begin exercising while wearing it. The other subjects performed for times ranging from 10% to 50% of the times they performed wearing the standard M17 mask, with an average of about 25%. The average performance time with the standard mask did not differ significantly from that with no mask.

Discussion

If filter life can be extended by exhaling through the filters, then there may be a choice for designers of emergency escape air-purifying respirator masks. By maintaining present filters, a 5-10 fold increase in filter life may be possible, and this might provide enough time margin to rescue trapped individuals. On the other hand, filters may be able to be redesigned to give the same filter capacity with 5-10 times smaller inhalation resistance. The M17 mask has a nominal inhalation resistance of about 3.4 cm H₂O • sec/L (4.8 cm H₂O at 85 L/min) and a nominal exhalation resistance of about 1.4 cm H₂O • sec/L (2.0 cm H₂O at 85 L/min). Rebreathing through the inspiratory filters could make possible a nominal inhalation and exhalation resistance of 0.3 to 0.7 cm H₂O • sec/L, lower than either inhalation or exhalation resistances are at present.

According to our results, the first choice, at least under the conditions of this study, may not be a good one. Three of the subjects were intimidated enough by the high exhalation resistance that they could perform no work. The other 70% for the subjects could only perform 25% of the amount of work that they could with a standard M17 mask.

However, if the subjects were trained in the use of high exhalation resistance masks, they might tolerate them much better. Also, in an emergency situation, wearers would probably be much more motivated to continue work with the masks on. It may also be true that our constant-rate work protocol was too severe. It seems possible that intermittent periods of high intensity work, separated by very low intensity work or rest, may be a more realistic situation to test.

There should be no question that breathing through a high exhalation resistance will incur significant energetic costs. At some point there is a limit to the rate of work (as given by maximum oxygen uptake) that any human can perform, and if a larger share of the limit is used to breathe, then a smaller share will be available to perform external work with the skeletal muscles. Even worse, the muscular efficiency of the respiratory muscles is about one-half that of the larger groups of skeletal muscles (Johnson, 1991). Thus, each unit of extra breathing work requires that two units of skeletal muscle work not be performed.

Table 1. Descriptive statistics for ten subjects.

Age (yrs)	22.6 ± 4.7
Mass (kg)	63.6 ± 10.1
Height (cm)	159.9 ± 32.6
Resting heart rate (beats/min)	62.8 ± 5.8
Maximum heart rate (beats/min)	194.1 ± 6.9
Maximum oxygen uptake (L/min • kg)	47.0 ± 6.6
Trait anxiety score (pretest)	28.9 ± 4.1

Values are means ± standard deviations.

Table 2. Test results.

Subject	Performance times (minutes)		
	No mask	Standard mask	High resistance mask
1	14	21	0
2	34	35	3
3	10	10	0
4	6	7	3
5	20	19	10
6	30	15	2
7	34	31	5
8	10	8	3
9	10	11	2
10	8	5	0
Average ± Std dev	17.6 ± 11.1	16.2 ± 10.3	2.8 ± 3.0 (4.0 ± 2.8) *

*Average and Standard Deviation excluding those subjects who could not exercise at all.

All this could translate into abandonment of the idea of exhaling through the inspiratory filters, except that the payoff for this type of breathing, at

least for certain situations, is potentially so high. This idea may still deserve another look.

Conclusion

Exhaling through the inspiratory filters of an air-purifying respirator mask could potentially increase the capacity of the filter to remove 5–10 times the amount of airborne contaminant compared to unidirectional flow through the filter. It was found, however, that subjects do not readily accept this type of breathing and can exercise only about 25% of the

time that they can wearing a standard mask at a constant work rate eliciting 75–80% of their maximum heart rate.

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