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Review of Recent Research On Respiration While Wearing a Respirator

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Abstract

Recent experiments relating performance to respirator resistances and dead volumes have been reviewed. Effects of each of these were most pronounced at very high work rates, where there were linear relationships between performance times and resistance or dead volume levels. There did not appear to be any threshold levels of resistances or dead volumes below which there were no performance effects. Thus, no optimum target values could be identified.

Introduction

Respiratory effects are the first to be noticed when putting on a respirator. Air-purifying respirators interpose a filter between the wearer and the atmosphere that impedes inhalation. The exhalation valve makes exhalation more difficult, especially in moist conditions where the valve can stick closed until a higher than normal pressure is reached. Dead volume in the respirator facepiece accumulates carbon dioxide rich and oxygen poor air from the previous exhaled breath and returns it to the lungs during the subsequent inhalation. Partially to ameliorate these difficulties, powered air-purifying respirators, self-contained breathing apparatus, and airline respirators are sometimes used.

Early investigators were very concerned with the respiratory burdens of respirators (Silverman *et al.*, 1945; Van Huss and Heusner, 1965; Demedts and Anthonisen, 1973; Flook and Kelman, 1973; Cummings *et al.*, 1958; Cummings *et al.*, 1969; Jackson and Cummings, 1972; Craig *et al.*, 1968; Craig *et al.*, 1970; Johnson and Berlin, 1973), and attempted to define acceptable limits to resistance levels (Cooper, 1960). One major difficulty with these early attempts was that increased resistance levels did not always yield meaningful reductions in exercise performance. We now know that this was due to large variations of

experimental conditions, resistance levels, equipment, and testing protocols. Dead volume effects and resistance effects were not separated; temperature conditions were not held constant; effects of vision impairment were not controlled; and anxiety levels of subjects were not determined. Perhaps most important of all, exercise conditions were not employed that were most sensitive to respiratory stress (Babb *et al.*, 1989; Demedts, and Anthonisen, 1973).

An example of this is the published work by Deno *et al.* (1981), wherein work performances of individuals wearing masks with various resistance levels were tested. Their short term test protocols kept neither work rate nor total time constant; their prolonged exercise protocol was very insensitive to resistance effects. Thus, interpretation of their results cannot be made easily.

Johnson and Cummings (1975) first proposed the idea that only very heavy exercise would be most sensitive to respiratory stress. Experimental data further defining the region of predominant respiratory stress was presented in a paper by Johnson (1976). Indeed, when Stemler and Craig (1977) tested exercise performances of individuals wearing respirators with different levels of

resistance, they found unequivocal evidence that higher resistances caused lower performance times. Key to their experimental procedures was that they imposed constant levels of work rate that resulted in performance times of 6–15 minutes.

Aside from the work performance aspect, resistance also affects comfort of respirators. Bentley *et al.* (1973) tested 158 mine rescue workers and determined that 90% of the population breathing through an apparatus with low resistance expiration valves should experience no discomfort if the pressure swing at the mouth did not exceed 17 cm H₂O. There are several reasons why comfort has not been used as the primary determinant of resistance effects in the studies to be reviewed: 1) it is subjective, 2) it does not predict work performance, and 3) comfort is most important at resting and low work levels when there is time to think about such things. Thus, Johnson *et al.* (1992) proposed the Performance Rating Table as a means to organize experimental

procedures to separate effects of different mask factors and work rate levels. They recognized task performance as the most legitimate measure of respirator effects, and proposed a means to obtain overall respirator performance decrements from component contributions at different work levels. Because different mask factors such as vision, respiration, communications, thermal effects, personal support, other equipment compatibility, and anxiety level each are important at different work rate levels, experiments must be performed at constant work rates; non-constant work rates integrate different contributions by different mask factors and are not able to isolate effects of one factor only. Thus, the studies to be reviewed here are those where: 1) external work rates were maintained constant at a level designed to be most sensitive to respiratory stress (usually 80–85% of VO₂max), 2) wide ranges of resistances and dead volumes were tested in order to be able to discern trends that could otherwise be obscured by experimental variations.

Effect of Inspiratory Resistance

Twelve volunteer subjects walked on a treadmill at 80–85% VO₂max until their voluntary end points (Johnson *et al.*, 1999). They wore US Army M17 full-facepiece air-purifying respirators with filters modified to give six different levels of inspiratory resistance ranging from 0.78 to 7.64 cm H₂O • sec/L (1.11 cm H₂O to 10.82 cm H₂O at 85L/min. flow rate). Treadmill speeds and grades were maintained at constant levels for each subject throughout all replications despite the fact that oxygen consumption decreased as resistance level increased.

Results (Fig. 1) show that performance time decreased linearly as inspiratory resistance increased. The wide range of resistances used in this study allowed unequivocal resolution of the dependence of treadmill walking time on inspiratory resistance. In terms of performance rating, defined as the ratio of task performance with a respirator divided by performance of the same task without a respirator, expressed as a percentage,

$$\text{Perf rating} = 100 - 8.73 (\text{Resistance}) \quad (1)$$

where resistance units are cm H₂O • sec/L.

This equation includes effects of mask factors in addition to inspiratory resistance level and so may be somewhat specific to the M17 respirator. Nonetheless, the linear dependence of heavy work

performance on inspiratory resistance would be expected to remain true for all air-purifying respirators, and possibly for other respirator types as well.

It did not appear from the data that a resistance threshold value existed below which resistance would have no effect on performance time. Thus, all resistances reduce performance.

Also measured in this experiment were respiratory minute volumes, oxygen consumptions, and breathing apparatus comfort. Minute volumes and oxygen consumptions decreased linearly as resistance increased. Thus, increased inspiratory resistance is accompanied by hypoventilation. Contrarily, as resistance decreases, wearers pull more air through the filters, decreasing filter contaminant breakthrough times.

As a consequence of the resistance-hypoventilation relationship, experimental control conditions that include any resistance whatsoever (including half masks or pneumotachs used to make respiratory flow rate measurements) will decrease performance times. Thus, control conditions must be carefully planned.

Also, because equation (1) is valid for resistance changes, as long as all other respirator conditions and configurations remain the same, studies such as the one performed by Stemler and Craig (1977), where

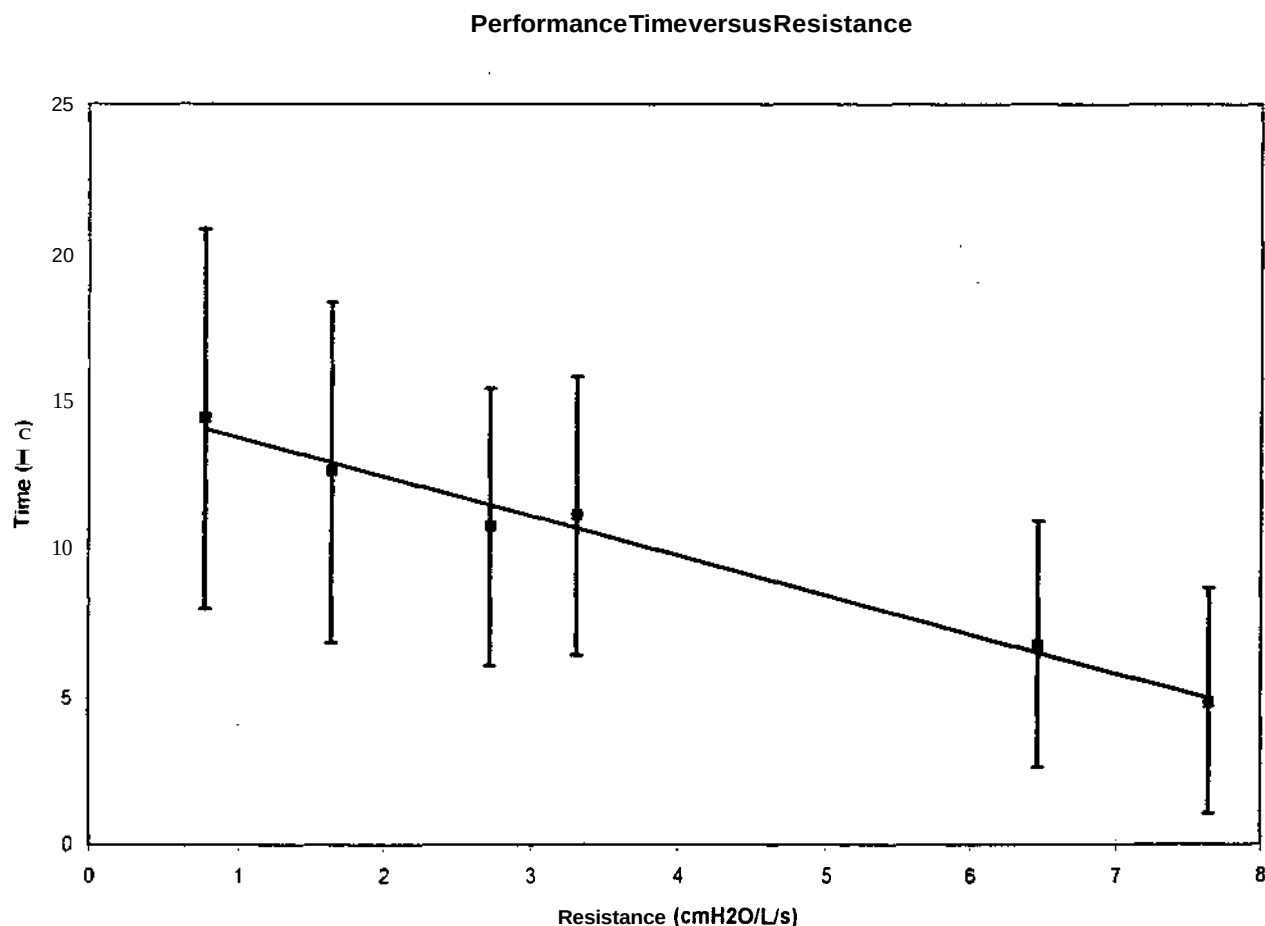


Figure 1. Treadmill performance times for subjects working at 80–85% $\dot{V}O_2\text{max}$ with various inspiratory resistance values.

different respirator facepieces were used, could not be used to discern a linear resistance-performance time relationship.

Caretti and Whitley (1998) performed a similar test with a half mask rather than a full-facepiece respirator. They used four inspiratory resistances ranging from 1.4 to 3.5 cm H₂O • sec/L, measured at 85L/min airflow. However, rather than maintaining a constant treadmill speed and grade for all conditions, they attempted to maintain oxygen consumption constant. Because oxygen consumption was found by Johnson *et al.* (1999) to decrease with increased resistance, Caretti and Whitley (1998) had to increase actual physical work rate that subjects performed at higher resistance levels in order to hold oxygen consumption constant. This resulted in a resistance-performance time relationship that was more severe than the linear relationship found by

Johnson *et al.* (1999A). Nonetheless, Caretti and Whitley (1998) did find that performance time and minute volume decreased as resistance increased.

The decrease of treadmill performance time with increased inspiratory resistance was confirmed with commercially-available air-purifying respirators (Johnson *et al.*, 1999B). Twelve volunteer subjects walked on a treadmill at 80–85% of age-predicted maximal heart rate (71–79% $\dot{V}O_2\text{max}$) until their voluntary end points. Test conditions were bare-headed, Racal Air Mate 3 loose fitting respirator, North 76008A full-facepiece respirator, and US Army M17 full-facepiece respirator. As expected, performance times were lower for the respirators with higher inspiratory resistances. No attempt was made to equalize other differences in the respirators, including weight, vision, and physical configurations.

To further illustrate that experimental conditions greatly influence the relationship between resistance and performance, Johnson *et al.* (1995) performed a graded exercise study (work rate progressing with time) with three respiratory conditions: 1) a standard US Army M17 full-facepiece air-purifying respirator with 3.4 cm H₂O • sec/L resistance, 2) a half mask condition meant as a control that had 0.7 cm H₂O • sec/L resistance, and 3) a mouthpiece control with 0.6 cm H₂O • sec/L resistance. Although there was a considerable difference in resistances between the respirator and the two control conditions, there were no differences in performance times for any of the conditions. Scatter plots of both minute volume and oxygen consumption for the half mask vs. full mask conditions show that the effect of the respirator condition is different between rest and heavy exercise, and that hyperventilation at rest and low work rates becomes hypoventilation at high work rates. Thus, nonconstant work rates do not result in performance time dependency on resistance level.

If the work rate is not high enough, there is again no effect of resistance on performance time. Johnson *et al.* (1997) performed a study of 10 continuous hours of respirator wear. Subjects performed various tasks in three one-hour blocks. During the first hour they performed various cognitive and coordination tasks. During the second hour they rode a bicycle ergometer at an intermediate work rate of 60–65% of maximum heart rate (43–50% VO₂max). During the third hour they performed on a ski machine at a volitional rate that was about 70–75% of maximum heart rate (57–64% VO₂max). Tasks in one hour

blocks were performed in round-robin fashion throughout the day, beginning and ending with the cognitive tasks. Subjects performed these tests once wearing a US Army M17 full-facepiece respirator and once without a respirator. Despite the fact that work rates were held nearly constant for each of the hours, there was no discernable effect of the respirator wear on any performance measure for any of the tests. Thus, inspiratory resistance appears to have no effect on performance unless the work rate is high enough to tax the respiratory system.

Caretti (1999) reported on a study designed to determine whether respiratory muscle fatigue follows prolonged ventilatory work while wearing a respirator. Five male volunteers walked on a treadmill at 50–60% VO₂max for 120 minutes per session. Three different respirator conditions were used: half mask (inspiratory resistance of 0.66 cm H₂O • sec/L), US Army M40 full-facepiece air-purifying respirators with standard filters (3.25 cm H₂O • sec/L), and US Army M40 respirator with modified filters (1.57 cm H₂O • sec/L). Pulmonary function was assessed after each test session to determine peak inspiratory and expiratory pressures.

Caretti (1999) found no differences between peak pressures measured before and after testing. He concluded, therefore, that, at least for these resistance values and for the healthy subjects who participated in this test, there was no evidence of respiratory muscle fatigue that could be attributed to respirator wear.

Effects of Exhalation Resistance

Respirator exhalation resistance has not been treated as a major problem for air-purifying negative pressure respirators because exhalation resistances are only the result of exhalation valves, and they have relatively low resistances of 1–2 cm H₂O • sec/L. There was evidence, however, that sending expired air back through the filters could significantly improve filter life, and this could be of benefit during emergency situations. Johnson *et al.* (1997) tested ten volunteer subjects to determine what effect exhalation through the inspiratory filters would have on treadmill performance at 75–80% of maximum heart rate for each subject (about 70% VO₂max). Thus, exhalation resistance equaled inhalation resistance of about 3.4 cm H₂O • sec/L for the US Army M17 respirators used.

Performance times for the high exhalation resistance condition averaged about 17% of those for the standard respirator condition. Three of the subjects could perform no work at all with the high exhalation resistance, and, of the remainder, only 25% of the work performed with the standard respirator could be performed with the high exhalation resistance.

Caretti *et al.* (1993) conducted an evaluation to determine whether or not there was any value in replacing the expiratory valve of a prototype US Army respirator with a resistance of 1.4 cm H₂O • sec/L with a valve that produced a resistance of 0.6 cm H₂O • sec/L. The results of this study indicated that performance times, as

determined by treadmill walking at an intensity of 80% VO_2max , did not differ between the two expiratory resistance conditions. Other than tidal volume, which was significantly greater for the low resistance condition, no significant differences in minute volume and oxygen consumption were observed between the test conditions. From these findings, Caretti *et al.* (1993) concluded that incorporation of the lower resistance valve into the new respirator would provide no substantial performance benefits to the end users.

Caretti *et al.* (2000) performed a more systematic study of the effect of exhalation resistance. They tested 16 volunteer subjects between the ages of 19 and 33 years. Subjects exercised on a treadmill at 80-85% of VO_2max until their voluntary end points with six different exhalation resistances ranging from 0.27 to 27.35 $\text{cm H}_2\text{O} \cdot \text{sec}/\text{L}$ measured at 85L/min. US Army M40 negative pressure air-purifying full-facepiece respirators were used with approximately 3.17 $\text{cm H}_2\text{O} \cdot \text{sec}/\text{L}$ inspiratory resistance for all exhalation resistance conditions. Treadmill speeds and grades remained the same for all resistance conditions.

Results (Fig. 2) indicate that performance time decreased linearly as exhalation resistance increased. The range of resistances used in this study again helped to define the overall trend in the data. Performance rating effects were:

$$\text{Perf rating} = 100 - 2.41 (\text{Resistance}) \quad (2)$$

where resistance units are $\text{cm H}_2\text{O} \cdot \text{sec}/\text{L}$.

As with inspiratory resistance, there was marked hypoventilation that was linearly related to exhalation resistance level. Both minute volumes and oxygen consumptions decreased as expiratory resistance increased. There were no statistically significant differences in breathing apparatus

comfort at termination for different exhalation resistance levels.

Combined Effects of Inspiratory and Expiratory Resistances

Comparing equation (2) with equation (1) demonstrates that the coefficient multiplying resistance value is greater in equation (1), possibly signifying that inspiratory resistance has a greater effect on performance than does expiratory resistance. Because these two tests of effects of inspiratory and expiratory resistances were performed with two different respirator facepieces, it is possible that the two equations cannot be compared directly. However, the expression of performance as performance ratings should account for many of the differences due to different equipment.

Caretti (1996) made a limited attempt to determine the effects of different inspiratory and expiratory resistances on performance during constant load work using a half-mask respirator. In this study, exercise performance and subjective responses were measured on five subjects at four levels of inspiratory resistance (0.6, 1.4, 2.1, and 2.8 $\text{cm H}_2\text{O} \cdot \text{sec}/\text{L}$) combined with two levels of expiratory resistance (0.8 and 1.4 $\text{cm H}_2\text{O} \cdot \text{sec}/\text{L}$). Treadmill speeds and grades were maintained at constant levels for each subject throughout all test sessions.

Results showed that performance times decreased linearly with inspiratory resistance levels for both expiratory resistance conditions. There were no significant differences in performance times observed between the two expiratory resistance levels for each inspiratory resistance level.

Effect of Dead Volume

Thirteen volunteer subjects participated in a treadmill walking experiment at 80-85% of VO_2max (Johnson *et al.*, 2000). Five different dead volume treatments plus a control condition were randomly given to the subjects on different test days. Each dead volume was developed by modifying a US Army M17 air-purifying full-facepiece respirator. In some cases modifications involved no more than removing nose cup valves; in other cases extra tubes were added. Care was taken to maintain inhalation and exhalation resistances at the standard value for the M17 respirator.

The control condition consisted of a Hans-Rudolph half mask that had 377mL of dead volume. Thus, it was not a particularly good control condition because of its high level of dead volume, but it did provide additional data.

Dead volumes were measured by determining carbon dioxide concentrations and respired volume while the apparatus was worn by the subject. This method is inherently unstable and results in dead volume measurements with a great deal of variability. Average dead volumes for each condition were

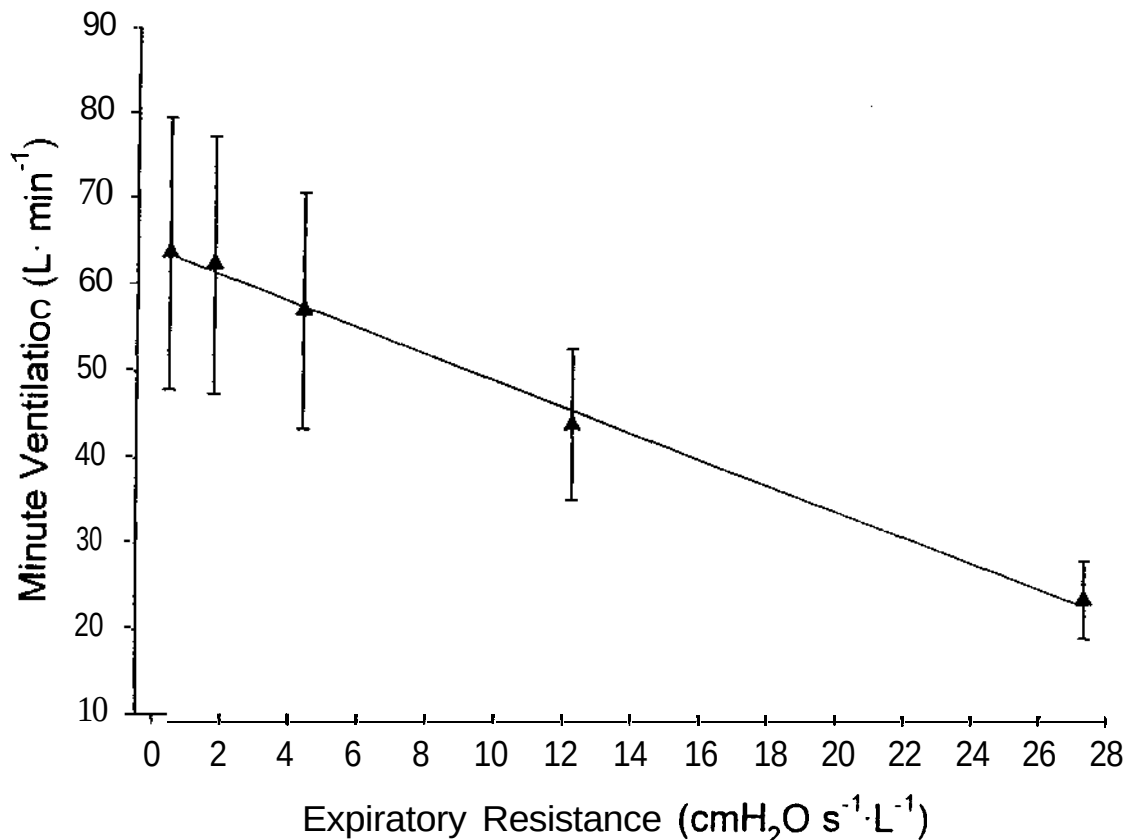


Figure 2. Minute ventilation for subjects working at 80–85% $\dot{V}O_{2\max}$ with various inspiratory resistance values.

288, 377 (control condition), 381, 445, 645, and 1162mL. Actual dead volume measurements were used in data analysis.

Subjects walked until their voluntary end-points. In Fig. 3 are shown data of performance rating as a function of external dead volume. The relationship between performance rating and dead volume is linear:

$$\text{Perf rating} = 100 - 0.055 V_D \quad (3)$$

where performance rating is the ratio of a performance measure while wearing the respirator compared to no respirator performance, and V_D is external dead volume in mL. As with resistance, there was no apparent threshold value below which dead volume had no effect.

Equation (3) indicates that performance rating becomes zero at a dead volume of about 1800mL, and can be negative at dead volumes greater than 1800mL. Dead volumes greater than tidal volume can have no additional effect because no exhaled air

escapes beyond the dead volume, and all inhaled air has previously been exhaled into the dead volume. Tidal volumes of 1800–2000mL are fairly typical values for subjects working at 80–85% max. Thus, performance ratings cannot be negative, but can remain at zero for dead volumes greater than tidal volume.

Inhaled carbon dioxide is a powerful respiratory stimulant. We might expect that the excess carbon dioxide accumulating in the respirator dead volume would result in faster or deeper breathing. The larger the dead volume, the greater the amount of rebreathed CO_2 . Stannard and Russ (1948) determined that there was almost complete respiratory compensation at rest to mask dead volume by a tidal volume increase. No differences in oxygen consumption or minute volume were found by Johnson *et al.* (2000) as a result of added dead volume during exercise. This contrasts to the hypoventilation induced by external inhalation resistance. Thus it was concluded that the physiological effects on breathing of resistance are more pronounced than those due to dead volume.

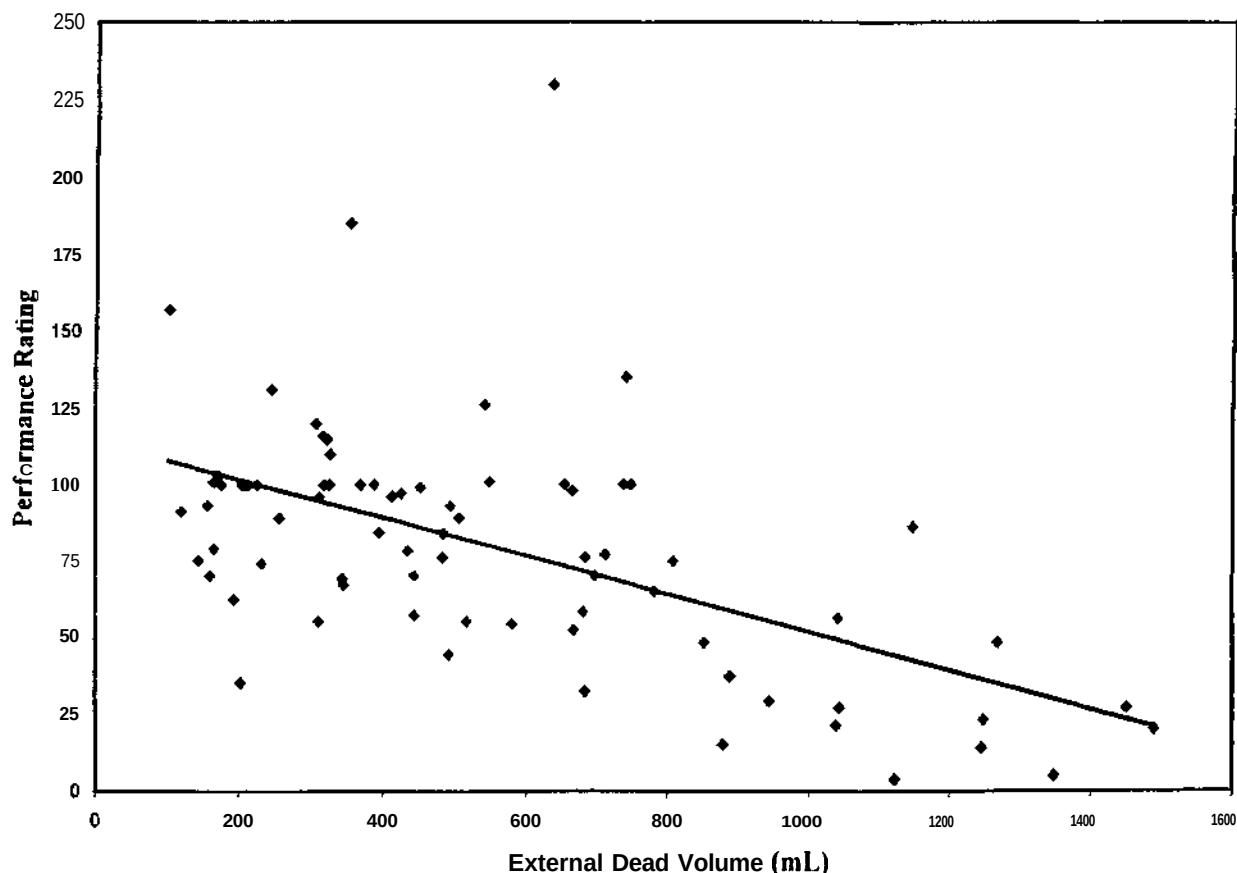


Figure 3. Performance rating for subjects working at 80–85% $\dot{V}O_2$ max with various levels of external dead volume.

The highest dead volume treatments were found to be very uncomfortable to several of the subjects.

Breathing apparatus comfort was inversely related to external dead volume.

Conclusions

There have been numerous past attempts to determine target values for inhalation and exhalation resistances and dead volume for respirator masks. Research reviewed in this paper indicates that no such values can be recommended. All external resistances and dead volumes affect exercise performance times at high work rates. At lower work rates, there is diminished effect of resistance, at least.

Respirator discomfort is directly related to levels of resistances and dead volumes in the respirators. Prescription of respiratory protection for an individual should probably be based on the lowest resistances and dead volumes available while still maintaining adequate protection. However, if the discomfort of greater than minimal resistance and dead volume can be tolerated, then there is

probably no performance penalty to be paid except at very high work rates.

Designers of filters strive for low resistance. However, lower resistance is accompanied by higher minute volumes. Thus, lower resistance filters will probably have more rapid contaminant breakthrough. How significant is this difference cannot be answered here.

There are still unanswered questions. The relative effects of inhalation and exhalation resistances are not known, the relative effects of dead volume and resistances are not known, and the contribution of respiratory condition of the wearer on resistance and dead volume effects are not known. These questions will be the subjects of upcoming experiments.

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