

How Is Respirator Comfort Affected by Respiratory Resistance?

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ABSTRACT

Comfort of respirators is an important determinant for their use in contaminated atmospheres. This study was intended to demonstrate the relationship between subjective comfort and resistance to inhalation air flow in the respiratory system (conventionally called "respiratory resistance"). Respiratory resistance was measured with the Airflow Perturbation Device, which is described briefly. Subjects sat quietly in a respirator with one of six resistance inserts, ranging from 0.2 to 33.3 cm $H_2O \cdot \text{sec/L}$, and breathed either through their noses or mouths. In all instances but one, respirator comfort decreased as respiratory resistance increased, and for the one remaining instance, the trend was very slight. It was concluded that respirator comfort is affected by the respiratory resistance of the wearer.

Keywords: respirator comfort, respiratory resistance, airflow perturbation device

INTRODUCTION

According to the Weber-Fechner Law (Ganong, 1963; Smith, 1998), the detection of an additional increment of a sensory stimulus depends on the level of the stimulus already present. Perception of differences in light intensity and the loudness of sound varies in proportion to the existing levels. In 1978, Burki et al. published a paper that indicated that detection of added breathing resistance also varied proportionally to the existing level of resistance. Gottfried et al. (1978) came to a similar conclusion. O'Connell and Campbell (1976), in attempting to determine the nature of dyspnea for patients hospitalized with respiratory disorders, discovered that, if the pressure developed in the respiratory system to draw air into and out of the lungs exceeded about 14% of the maximum pressure that could be produced by the respiratory muscles, a feeling of breathlessness and difficult breathing was evident. Raven et al. (1981) tested respirators on patients with pulmonary function deficiencies. For those patients with severe flow rate impairment, the respirators had little or no hypoventilatory effect, as they do for normal wearers.

It seems plausible, therefore, that a person's internal respiratory resistance can have a large influence on the degree to which a respirator affects the wearer. It would be expected that respirators would have less influence on people with higher internal respiratory resistances, because the added resistance of the respirator would represent a smaller proportion of the higher internal respiratory resistances already present.

Over the years and in the course of many tests, it has been observed that some people seem to be affected more by respirators than others. The result is a large variability in individual responses to respirator wear. It is likely that this variability exists in the workplace and in the population as a whole. Is

there a way to determine which potential wearers are more likely to accommodate respirator wear, and thus be able to perform better the tasks that they are assigned while wearing respirators? Or, is there a personal limitation to the improvement that can be expected in response to training programs? These are questions of importance as workers, first-responders, and military personnel attempt to improve their effectiveness while wearing respirators.

Respirator comfort is a subjective measure that can have many different meanings. It is likely that respirator comfort is most important for sedentary or light-work tasks (Johnson et al., 1992) where the attention of the wearer can be directed somewhat inwardly. Comfort, however, has a detection component, and, based on the published information cited previously, it might be expected that wearers with higher levels of internal respiratory resistance would be less likely to detect the added respirator inspiratory resistance, and thus be less likely to attribute discomfort to the respirator.

Most standard pulmonary function tests do not directly measure respiratory resistance. The Airflow Perturbation Device (APD) was developed as an instrument to measure respiratory resistance directly (Lausted and Johnson, 1999). It does this by measuring both respiratory air flow and mouth pressure while a rotating wheel with screened and open segments perturbs flow and pressure by small amounts (Figure 1). The sizes of the perturbations depend on resistance in the device and in the respiratory system. Because both flow and pressure are measured, resistance of the device is known; respiratory resistance can then be calculated easily.

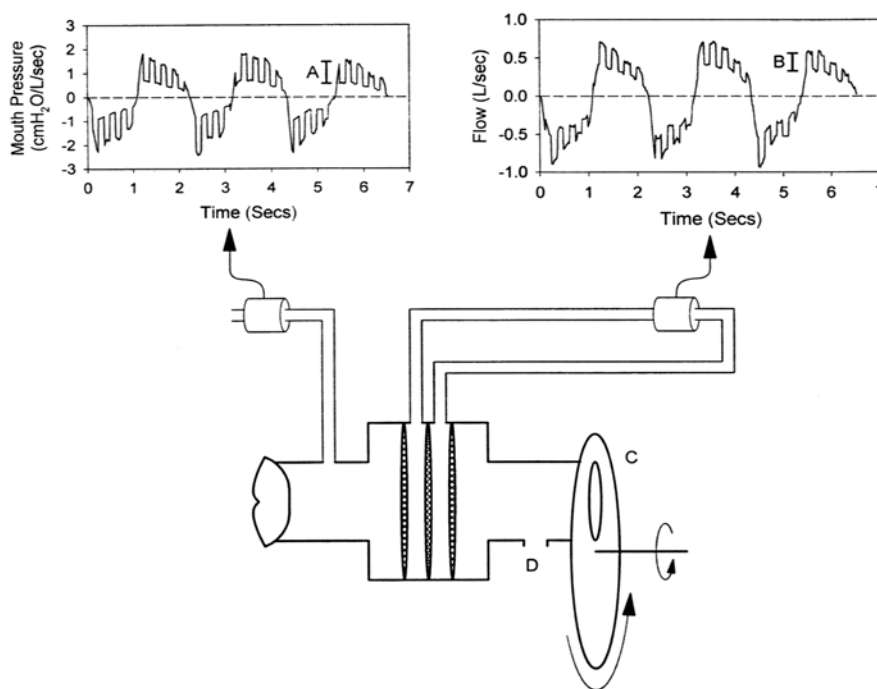


Figure 1. Diagram of the APD. As the wheel rotates in the flow pathway, it presents regions of higher and lower resistance. These induce changes, or perturbations in mouth pressure and air flow rate. The ratio of pressure perturbation (A) magnitude to flow perturbation magnitude (B) is the resistance to air flow in the respiratory system.

The APD is small and lightweight. It is completely noninvasive and requires no more than normal breathing. Resistance is normally measured through the mouth, with a nose clip and hands pressed against the cheeks. Data are analyzed in real time by computer and displayed as averages of the last few perturbations. Values appear within a minute from starting the measurement. They are thereafter updated as they occur. Resistance in the inhalation and exhalation directions can be separated, thus giving diagnostic information related to specific respiratory diseases.

With the ability to directly measure the resistance to inspiratory air flow, this experiment was conceived to test the hypothesis that respirators would be more comfortable at rest for wearers with higher internal inspiratory resistances.

METHODS

Fourteen subjects (7 males and 7 females) between the ages of 18 and 35 volunteered to participate in this study. Subjects were recruited from the University of Maryland student body. The protocol was approved by the University of Maryland Institutional Review Board and all subjects signed a statement of informed consent prior to testing.

Subjects received a verbal orientation to the testing at the start of the first session. In addition, a variety of pulmonary function tests were performed at this time. Respiratory resistances were measured with the APD. Mouth resistance was measured while subjects breathed through a standard cardboard disposable mouthpiece fitted to the APD. A noseclip occluded flow from the nose. Nasal resistance was measured separately using an oronasal mask attached to the APD (Wong and Johnson, 2004). The mouth was closed during nasal breathing. Subjects were selected to represent a wide range of resistance values in order to extract trends from natural variability.

Volunteers were fitted with a military-style negative pressure respirator (FR-M40; 3M; St. Paul, Minn.), which was modified to produce six different inspiratory resistances. External modification of the inspiratory resistance level was accomplished through the addition of resistance orifices, ranging from 0.2 to 33.3 cm $H_2O \cdot \text{sec/L}$ (Table I). The orifice inserts replaced filter cartridges before the inhalation valve on the respirator. These resistance values had been used in previous studies (Johnson et al., 1999) and represent a wide range of resistances. The highest resistance value is more than 150 times greater than the lowest resistance. The Rstd resistance is typical of an air-purifying respirator.

Two sessions were conducted with each subject. In one session, subjects breathed only through the nose, while in a second session subjects were instructed to breathe solely through the mouth; the session order was randomized across all subjects.

Table I. Respiratory Insert Inhalation Resistance Values Measured for Each Resistance at 6 L/min

Insert	Inhalation Resistance at 6 L/min (cmH ₂ O/L/sec)
Rstd	0.749
R0	0.213
R1	1.103
R2	1.305
R3	10.870
R4	33.264

During each session, the subjects were first introduced to the various resistance conditions through two-minute practice stages. This allowed subjects to experience the full range of resistances that they would later be asked to judge. While seated, each subject donned a respirator, outfitted with a randomly chosen inspiratory resistance insert, and breathed normally via the method prescribed for the session (nose or mouth). Participants were asked to define their level of breathing apparatus comfort

each minute (starting at minute 0) using the Breathing Apparatus Comfort Scale (BACS) as shown in Figure 2. Upon completion of the six practice trials, test trials were then initiated.

Breathing Apparatus Comfort Scale (BACS)

10	Very, very comfortable
8	Very comfortable
6	Fairly comfortable
4	Fairly uncomfortable
2	Very uncomfortable
0	Very, very uncomfortable

Figure 2. The breathing apparatus comfort scale (BACS).

Test trials proceeded in a similar manner, the protocol differing only in the length of time in which volunteers were exposed to each resistance condition. Test stages lasted five minutes, as opposed to two. During the test, subjects sat still and did nothing else. Test trials were conducted for all of the resistance conditions in a random order.

All sessions were conducted in a controlled laboratory setting in the Human Performance Laboratory at the University of Maryland, College Park. The respirators were cleaned with alcohol and cotton pads between each subject.

The resistance of each orifice insert was measured using one subject. The volunteer was fitted with a respirator mask, modified for each condition, and was asked to breathe deeply for thirty seconds. Air flow and pressure data were collected for each thirty second period by means of hoses connected to the inhalation and exhalation ports of the mask. Air flow was measured using a computer connected to a Fleisch #3 pneumotach (OEM Medical; Richmond, VA) and a Validyne transducer (model DP 15; Northridge, Calif.). Pressure data were collected by attaching a tube to the mask through a pressure port. In addition, a DAS-8 analog-to-digital converter board (MetraByte-Keithley; Cleveland, Ohio) was utilized, as was a custom-designed computer program for measuring the air pressure and flow.

Each thirty second sample resulted in a data set containing approximately 1500 data points. For each measurement, exhalation and transitional data points were removed. Exhalation points were identified as those points in which both pressure and flow were positive, indicating air flow toward the pneumotach. Data points showing positive pressure and negative flow, or negative pressure and positive flow, were identified as transitional points. Therefore, only points that were negative for both pressure and flow, representative of inhalation with air flow away from the pneumotach, were considered.

The new data sets, containing only inhalation data points, were then graphed. All data points were first inverted by multiplying by negative one. A second-degree polynomial line was fitted through the data points and set to intercept the origin using Excel (Microsoft; Seattle, Washington). The Rohrer equation (Johnson, 1991) was then employed to define a pressure (P , cm H₂O) and flow ($\dot{V}$, L/min) relationship:

$$P = K_1\dot{V} + K_2\dot{V}^2$$

The values for K_1 and K_2 were determined using the second-degree polynomial line fit to each graph.

The relationship between pressure and flow for each resistance insert was nonlinear. Resistances of the inserts, defined as the slopes of the pressure-flow curves, could vary by as much as a factor of 10 between low flow rates and high flow rates. For this reason, resistances were evaluated at a

typical resting flow rate of 6 L/min. The best fit polynomial line was fitted to data between 0 and 12 L/min, and average resistance was calculated as the slope of the line drawn between no flow and 6 L/min flow rate (Figure 3).

The respiratory resistance of each subject was plotted against his/her specific BACS score at minute 5. Graphs were generated for each resistance condition during both oral and nasal breathing. The general trends of the data points suggested exponential fits (Johnson et al., 1995), and exponential lines were fitted through the data using Excel. In some cases for which Excel could not generate an exponential regression, a logarithmic line was fitted to the data.

RESULTS

Table II lists values of mouth and nose respiratory resistances for the 14 subjects who volunteered for this study. The ranges of mouth and nose resistances vary by multiples greater than 2. Standard values of average mouth resistance for about 1000 normal, healthy adults are in the range of 2.5 to 3.5 cm $H_2O \cdot \text{sec/L}$, with inhalation resistance normally lower than exhalation resistance (Johnson et al., 2002).

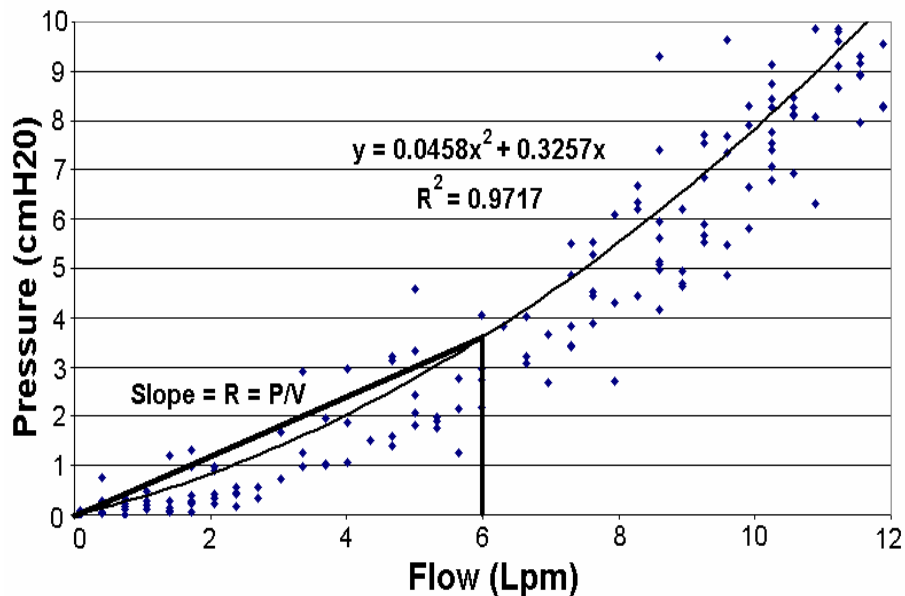


Figure 3. Flow vs pressure obtained for mouth breathing through the R4 resistance insert. The slope of the pressure-flow at 6 L/min of the best-fit curve has been taken as the resistance value of the insert.

Figure 4 presents BACS scores against internal inhalation respiratory resistance through the mouth for the R0 condition. An exponential curve has been drawn through the points as a guide to highlight trends. Exponential curves were used because they have been found to describe similar data over a wide range (Johnson et al., 1995). The degree of scatter of the data is common for subjective measurements (Johnson et al., 1995). Tables III and IV summarize best-fit equations for all respirator (external) resistance conditions for both mouth and nose breathing. All curves except one show a

downward trend as internal respiratory resistance increases. The one exception to this trend is for the R2 external resistance during mouth breathing that exhibits a very slight upward slope. These lines are plotted in Figure 5 for nasal internal resistance and in Figure 6 for internal mouth resistance.

Table II. Inhalation Resistance Values for Each Subject as Measured Using the APD

Subject Number	APD Inhalation Resistance (cmH ₂ O/L/sec)	
	Mouth	Nose
1	1.82	3.70
2	1.79	5.65
3	2.69	4.53
4	3.02	3.76
5	1.95	4.57
6	2.01	5.76
7	2.84	4.19
8	2.06	4.27
9	3.04	4.45
10	2.40	4.76
11	2.40	4.46
12	3.09	6.47
13	4.20	9.98
14	3.89	3.51
Average	2.66	5.00
Std. Dev.	0.75	1.66
Range	1.79 – 4.20	3.51 – 9.98

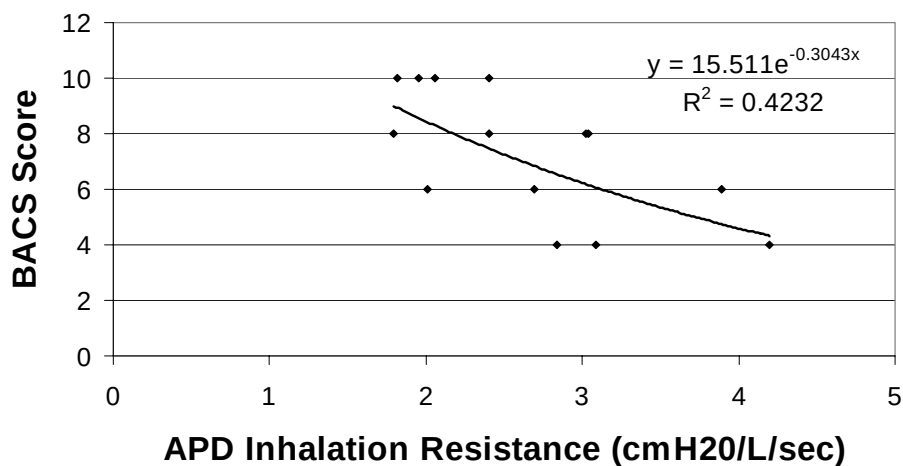


Figure 4. Breathing Apparatus Comfort Scale (BACS) score for each subject breathing through the R0 external insert respirator resistance condition. Internal respiratory resistance is plotted on the horizontal axis. BACS score was recorded during minute five of oral breathing.

Table III. Equations and R^2 Values for Regression Lines as Graphed for BACS Score (y) as a Function of Internal Inhalation Respiratory Resistance (x), Nose Breathing

Insert Condition	Equation	R-Squared (R^2) Value
RStd	$Y = 11.362e^{-0.1057x}$	0.2966
R0	$Y = 8.9487e^{-0.0677x}$	0.1883
R1	$Y = 14.337e^{-0.1718x}$	0.5367
R2	$Y = 10.053e^{-0.1323x}$	0.2890
R3	$Y = 6.4608e^{-0.0867x}$	0.0986
R4	$Y = -0.854\ln(x) + 4.1992$	0.0130

Table IV. Equations and R^2 Values for Regression Lines as Graphed for BACS Score (y) as a Function of Internal Inhalation Respiratory Resistance (x), Mouth Breathing

Insert Condition	Equation	R-Squared (R^2) Value
Rstd	$y = 11.786e^{-0.1911x}$	0.3353
R0	$y = 15.511e^{-0.3043x}$	0.4232
R1	$y = -4.202\ln(x) + 10.388$	0.2078
R2	$y = 5.1055e^{-0.0046x}$	0.0001
R3	$y = 6.0253e^{-0.1478x}$	0.0616
R4	$y = -1.1114\ln(x) + 3.6188$	0.0230

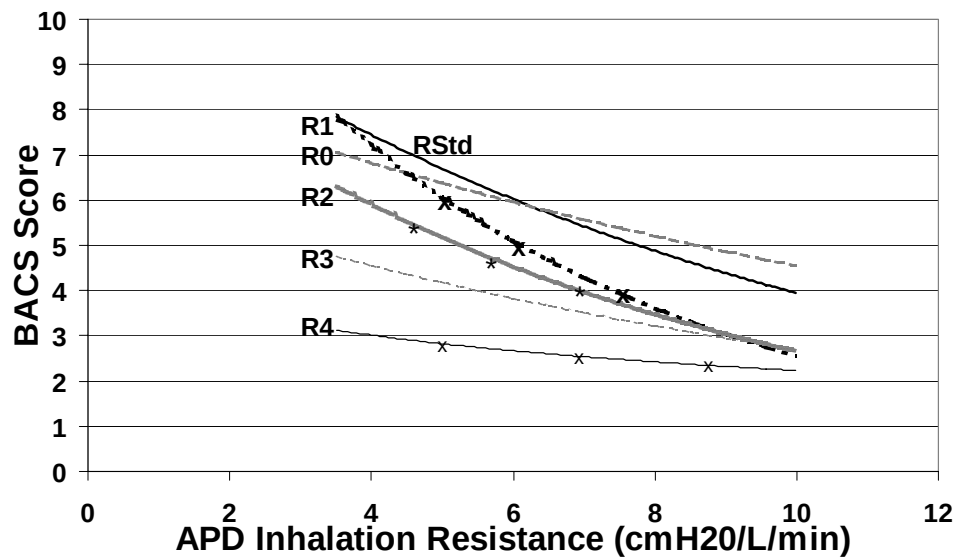


Figure 5. Regression lines plotted for Breathing Apparatus Comfort Scale (BACS) score at minute five as a function of internal nasal inhalation respiratory resistance. Each line represents a different respirator insert inhalation resistance.

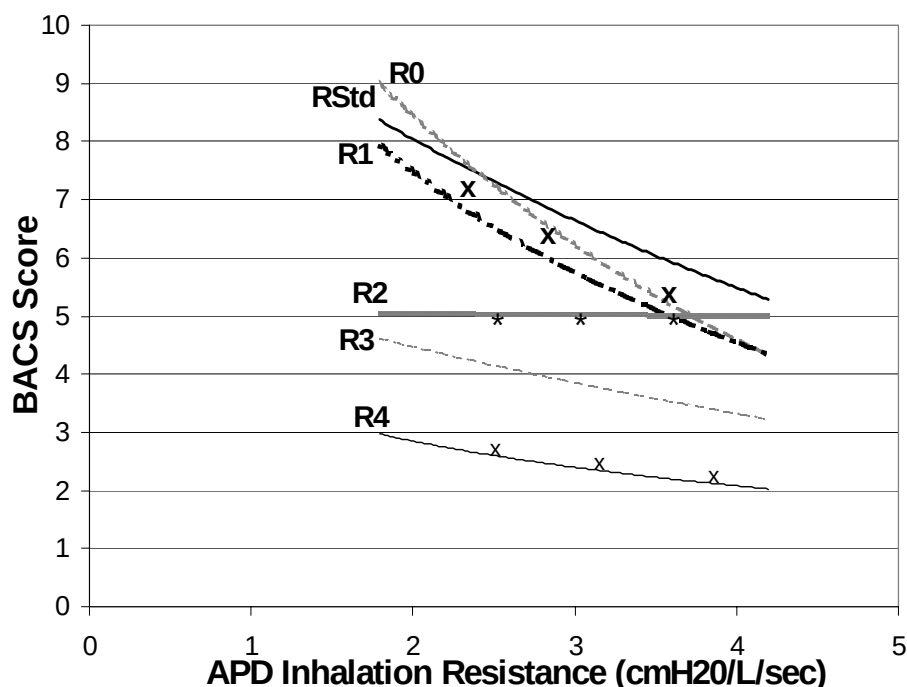


Figure 6. Regression lines plotted for Breathing Apparatus Comfort Scale (BACS) score at minute five as a function of internal oral inhalation respiratory resistance. Each line represents a different respirator inhalation resistance.

DISCUSSION

We have compared respirator comfort with respiratory resistance of the wearers. Several different respirator resistances were used. The original hypothesis, that respirators are more comfortable for wearers with higher respiratory resistances, has been proven untrue. In fact, it appears as if the opposite may be true. It is not clear why higher respiratory resistance should result in lower comfort ratings for respirators worn, and further investigation is warranted to determine causes.

As with many studies involving respirators, results from different subjects vary widely, and trends are weak. Some of this may be attributable to the subjective nature of the meaning of "comfort," which is defined individually. Another reason for the weak results is the crude cardinal nature of the BACS we used, and future studies will employ finer gradations. It is fortunate that several different levels of respirator inspiratory resistance were supplied, because the same trends can be seen at all external resistance levels. Thus, there is additional confidence that the exhibited trends of comfort versus internal respiratory resistance are reproducible.

Both oral and nasal breathing were used for this study for two reasons. First, some respirator wearers normally breathe through their noses; others breathe through their mouths. Second, nasal resistance is typically higher than mouth resistance (Wong and Johnson, 2004), extending the range of resistances tested in this study. A wide range of resistances is desirable in order to separate trends from background variation.

It is possible that, if subjects had been asked to detect respirator resistance differences, our results may have been entirely different. However, it seems that comfort of respirators is a more useful and important measure than ability to detect resistance differences.

When looking for real-life applications of these results, it must be concluded that the effects of internal respiratory resistance are not robust, and further testing could perhaps be useful. It does appear that people with pulmonary impairment might find respirator wear less comfortable than people with healthy respiratory systems. This may impact the types of respirators chosen for protection and the type of training given. These results indicate that the burden of respirator wear is likely perceived differently by different individual wearers. That may be the most important conclusion from this study.

CONCLUSIONS

Respirator comfort seems to be weakly related to internal respiratory resistance, with higher respiratory resistances corresponding to lower comfort.

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