
Respiratory Resistance Increases with the Addition of External Resistance Elements

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ABSTRACT

Respiratory protective masks are used by millions to guard against the inhalation of toxic contaminants. These add resistances to the respiratory circuit. Whether or not someone can successfully wear respiratory protective masks has been shown to be affected by the respirator mask inhalation and exhalation resistances. What is not completely known is the effect that adding external resistance to the breathing circuit might have on the person wearing the respirator. This exploratory study was conducted to determine what effect, if any, added external resistances have on human respiratory system responses.

The Airflow Perturbation Device (APD) was used to measure respiratory resistance of the human respiratory system in the presence of external resistance elements in increments of 1 cm H₂O·sec/L from zero up to 5 cm H₂O·sec/L resistance. It was determined that the addition of external resistance elements increased internal resistance in the exhalation direction at a proportional rate of 1.25 cm H₂O·sec/L per 1 cm H₂O·sec/L added external resistance, whereas internal resistance during inhalation increased proportionately at 1.18 cm H₂O·sec/L per 1 cm H₂O·sec/L added external resistance. The means of the inhalation resistance and exhalation resistance increments were found to be statistically significant utilizing a t-test with a p value of 0.05. The conclusion reached was that the wearer of a respiratory protective device is not passive, but reacts to the resistances of the respirator by increasing resistance of the respiratory system. Among other things, this finding may have implications for medical determination for who can successfully wear respiratory protective devices.

Keywords: respiratory resistance, respirator resistance, physiological effects of respirator wear, airflow perturbation device

INTRODUCTION

There are a number of respiratory protective devices currently used by those exposed to environmental contaminants, and, additionally, by wearers suffering from respiratory ailments such as asthma or COPD. Devices such as respiratory protective masks aim to reduce irritants entering the airways in order to improve breathing safety. Respiratory protective masks are designed to be placed over the nose and mouth to protect the user from vapors, gases, and other small particles that could enter the respiratory system. These devices are meant to be easy to use and comfortable enough to wear for long periods of time. Most, if not all, of these devices interpose flow resistances between the wearer and the surrounding atmosphere.

Typical air-purifying respiratory protective devices have inhalation resistances of 4 cm H₂O·sec/L and exhalation resistances of 0.1 cm H₂O·sec/L [Carette et al, 2006; Coyne et al, 2006]. This compares with typical human respiratory resistance of about 4 cm H₂O·sec/L, with resistance in the exhalation phase of breathing roughly 10% higher than during inhalation [Johnson et al, 2005]. Previous measurements with the Airflow Perturbation Device have averaged about 2.5 cm H₂O·sec/L for mouth breathing in adult males and about 3.5 cm H₂O·sec/L for mouth breathing in adult females [Johnson et al, 2005]. Human respiratory resistance while breathing through the nose was measured at about 4 cm H₂O·sec/L [Wong and Johnson, 2004]. These values illustrate that respiratory protective device resistances are of the same order of magnitude as are resistances naturally occurring inside the respiratory systems of the wearer.

The Airflow Perturbation Device (APD) is a small and compact device that allows its users to easily measure respiratory resistance during normal breathing [Lausted and Johnson, 1999]. The device is composed of a rotating wheel with open and closed segments, a pneumotach to measure breathing flow rate, and a mouth pressure transducer. The rotating wheel is used to temporarily partially restrict the air pathway, thus slightly changing, or perturbing, airflow and mouth pressure (Figure 1). The depths of perturbations depend on the APD resistance and the subject's internal resistance. The APD resistance is known from airflow and mouth pressure measurements, so respiratory resistance of the subject can be calculated noninvasively. The respiratory resistance value can be calculated by dividing the depth of pressure perturbation by the depth of flow perturbation.

The perturbations of the APD occur at a rate of about 10 per second. This change results in perturbations of airflow and mouth pressure that can be used to directly calculate respiratory resistance in nearly real time. Respiratory resistances during the inhalation phase of breathing can easily be separated from respiratory resistance during exhalation.

The APD used in this study was configured differently from that used in other studies [Haque et al, 2013; Holly et al, 2018; Johnson et al, 1984; Lausted and Johnson, 1999; Silverman and Johnson, 2005]. A new reference port location has been chosen to reference the pressure at the front of the APD rather than to the pressure of the atmosphere. This automatically excludes any resistance in front of the APD from the APD respiratory resistance measurement. The APD then measures only the resistance of the subject.

The APD reference pressure port is located in a non-flow dead space in order to measure true static pressure rather than dynamic pressure, as indicated by Bernoulli's equation. This has been done by attaching a cone obtained from a respiratory filter mouthpiece to the front of the APD. The new pressure port is located in the periphery of the cone, where the boundary layer flow is zero.

This study was exploratory in nature to determine if external resistances added to the breathing pathway of a human being had any responsive effect in the internal respiratory system of the person. If such responses were found, then there would be implications for wearers of respiratory protective masks.

The modified APD was used as the means to measure respiratory resistance responses within the humans tested.

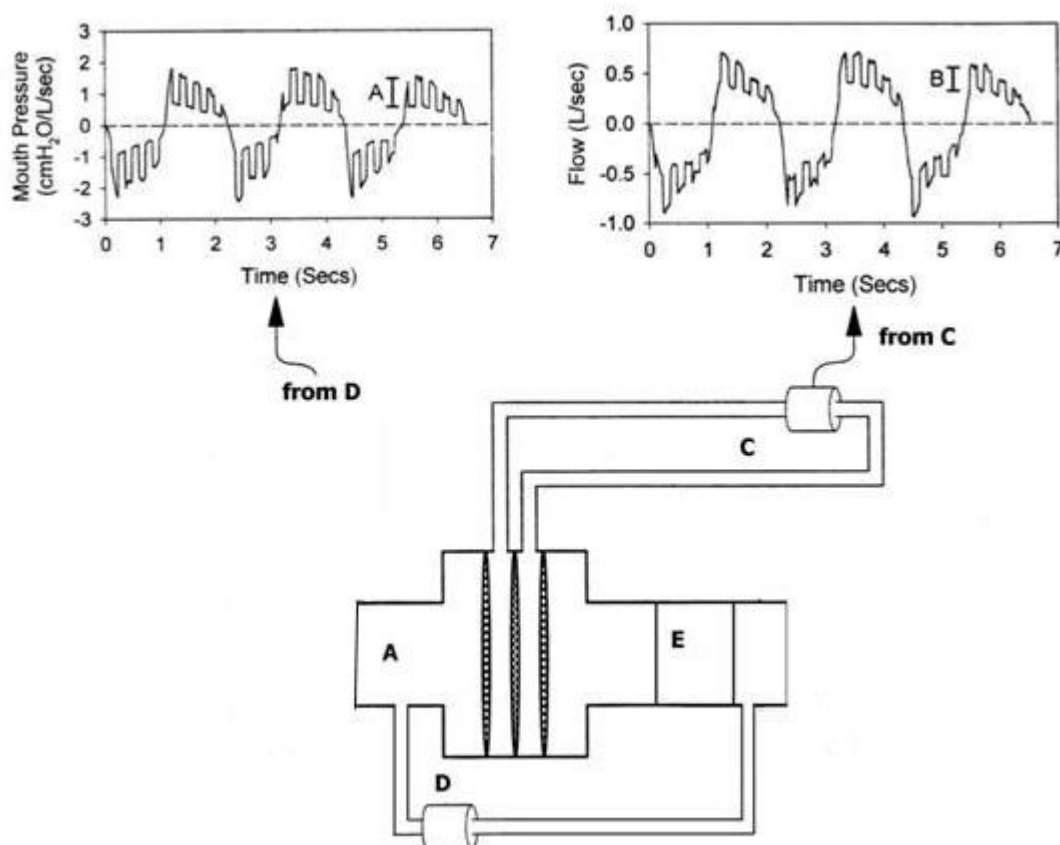


Figure 1. Diagram of the APD used in this study. The subject being tested breathes into the device at (A). Flow sensor (C) measures flow rate as it is perturbed by a perturbation mechanism (E) that consists of a rotating segmented wheel. Pressure sensor (D) measures mouth pressure. Diagrammed above are the tracings of mouth pressure and breathing flow as they are perturbed by the rotating wheel.

MATERIALS AND METHODS

This study measured respiratory resistance values by attaching a mouthpiece to the APD and having subjects breathe only from their mouth (Figure 2). Nose clips were used to seal the nasal passages while the subject breathed through the APD. Each subject was trained on how to properly use the APD in order to collect adequate resistance values as well as how to maintain a proper seal with the mouthpiece.

This study tested 25 volunteers of ages 18-22 while sitting at rest. A Health History questionnaire was administered to all potential subjects and none of the volunteers reported prior respiratory concerns such as snoring, congestion due to colds or other illnesses, or asthma. Voluntary consent was obtained from all subjects prior to their participation in the study. The protocol for this study was approved by the University of Maryland Institutional Review Board (IRB).

The linear resistance elements used in this study (Hans Rudolph, Kansas City KS) are made out of PET plastic and acetyl plastic, cylindrical in shape, with a diameter of 3.8 cm and a length of 8.25 cm, and each had a resistance value of 1 cm H₂O·sec/L. Resistance elements were added to the breathing circuit in front of the APD in groups comprising a total external resistance of 0 to 5 cm H₂O·sec/L. The order of how many resistance elements were being attached to the APD was randomized.

Dead volume in the breathing pathway accumulates exhaled carbon dioxide and returns it to the respiratory system during subsequent inhalations. This carbon dioxide can act as a respiratory stimulant and change breathing conditions during the test. Thus, total dead volume of the test apparatus had to be kept constant as resistance elements were added in order to eliminate confounding effects of different levels of carbon dioxide from the dead volumes of each resistance element.

In order to maintain constant the overall volume of the entire system, dead space volume elements were created. The dead volume space elements were created using cardboard tubes that were cut to the same length and diameter as the resistance elements. When zero resistance elements are attached to the mouthpiece, 5 dead space elements were attached to the mouthpiece linearly to simulate the total volume of 5 resistance elements. As resistance elements were added, dead space elements were removed to maintain a total of 5 resistance elements and/or dead space volume elements.

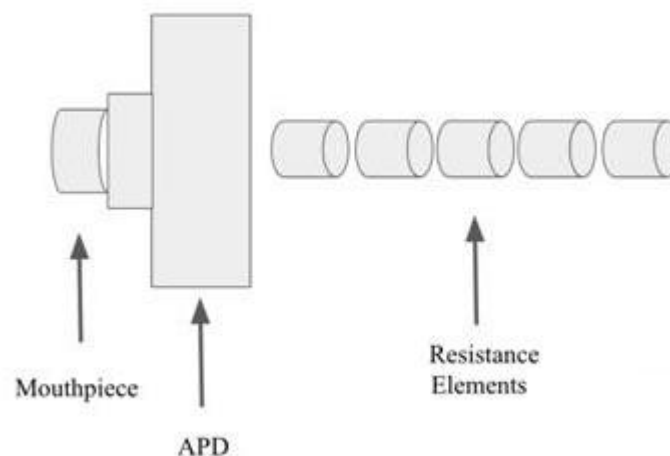


Figure 2. Diagram of the APD setup including all components required for the experiment to run.

In order to gain baseline data, participants breathed into the APD without any resistance elements or dead space volume elements attached. Participants breathed through their mouth into the mouthpiece for approximately a minute, the inhalation, exhalation, and average resistance values were displayed on the APD. These values were then recorded. After a 30 second break, this was repeated twice in order to average potential variation in data acquired [Johnson et al, 2012].

This process of breathing into the APD for approximately 1 minute with a 30 second break for three trials was conducted for each combination of resistance elements and dead space elements, for a total of 18 trials. The resistance values for all 25 participants were averaged such that there was a mean inhalation, mean exhalation, and overall mean for each combination of dead space elements and resistance elements.

RESULTS

Demographic information for all the volunteers is shown in Table I and Table II. The average baseline value among all subjects for average respiratory resistance (average of inhalation and exhalation resistances) was 3.66 cm H₂O·sec/L, the average height being 169.3 cm, and the average weight being 66.4 kg. Out of the 25 overall participants, 12 identified as male (48%) and 13 identified as female (52%) and all of the participants fell within the age range of 18-22.

The results for the Addition of Added External Resistance Elements to Subjects as They Breathed through the APD are summarized in Table III. The overall trend that was observed was that as the number of external resistance elements attached to the mouthpiece grew in number, both the inhalation and exhalation respiratory resistances of the subjects increased nearly linearly at an average rate of 1.18 cm H₂O·sec/L and 1.25 cm H₂O·sec/L per resistance element, respectively (Figures 3 and 4). In order to graphically display the data, the average inhalation and exhalation resistances were calculated for each number of resistance elements and plotted, with the slopes of the trend lines between those points acting as indicators of the rates at which the measured respiratory resistances increased.

Table I. The Average Height and Weight of Participants in Both English and Metric Units

	Avg. Height	Avg. Weight
English Units	66.84 in ± 4.41 in Range: 60-76 in	146.08 lb ± 26.72 lb Range: 102-201 lb
Metric Units	169.293cm ±11.42cm Range: 152-192 cm	66.36kg ±12.149 kg Range: 45-91 kg

Table II: Demographic Information of Participants. Participants Were Chosen within the Age Group of 18-22. The Base Inhalation and Base Exhalation Resistance Averages Are Shown in the Table.

Sex	Age (years)	Base Inhalation Resistance (cm H ₂ O·sec/L)	Base Exhalation Resistance (cm H ₂ O·sec/L)
52% Male 48% Female	18 (4%) 19 (12%) 20 (8%) 21 (40%) 22 (36%)	3.6036 ± 1.19 Range: 1.99-5.87	3.7088 ± .966 Range: 1.56-5.79

Table III: Results for the Addition of Added External Resistance Elements to Subjects as They Breathed through the APD, Separated by Subject Respiratory Resistances in the Exhalation and Inhalation Phases of Breathing

Resistance element(s)	Average Exhalation Resistance $\pm$ Std Deviations (cm H ₂ O·sec/L)	Avg Inhalation Resistance $\pm$ Std Deviations (cm H ₂ O·sec/L)
0	2.84 $\pm$ 1.08	3.23 $\pm$ 1.06
1	4.99 $\pm$ 1.16	5.41 $\pm$ 0.986
2	6.46 $\pm$ 0.962	6.93 $\pm$ 0.903
3	7.92 $\pm$ 1.22	8.07 $\pm$ 1.00
4	8.47 $\pm$ 1.04	8.71 $\pm$ 0.996
5	9.19 $\pm$ 1.09	9.30 $\pm$ 1.18

Average Exhalation Resistance

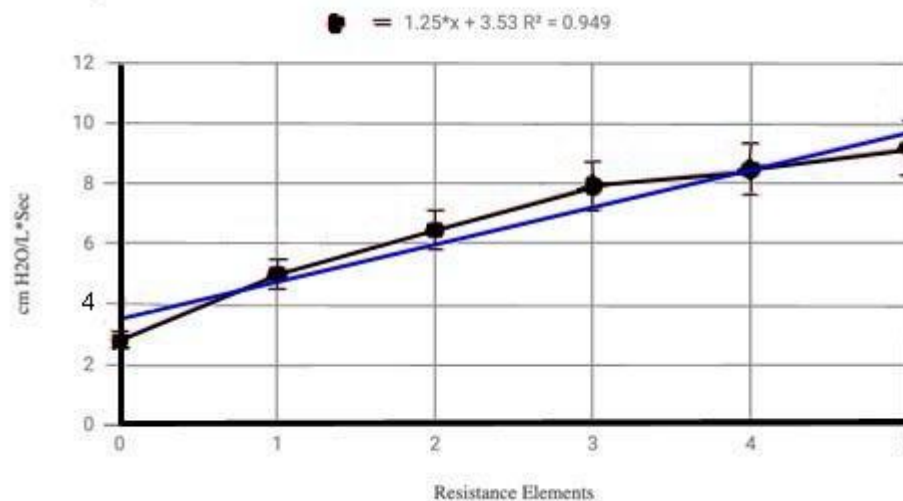


Figure 3: The average exhalation resistance for each number of resistance elements attached to the APD. The linear trend line shows a 1.25 cm H₂O·sec/L increase per resistance element. The R^2 value of 0.949 shows a 94.9% adherence to a perfectly linear relationship.

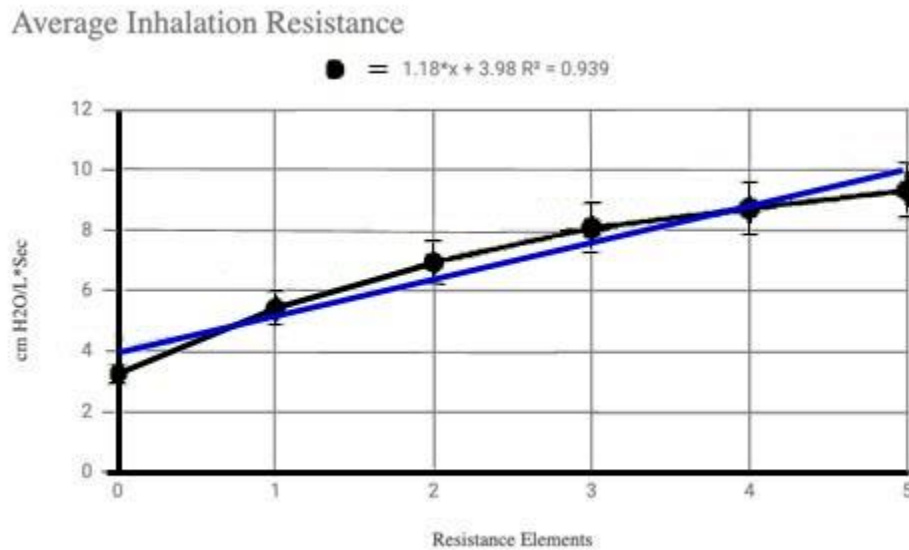


Figure 4: The average inhalation resistance for each number of resistance elements attached to the APD. The linear trend line shows a 1.18 cm H₂O·sec/L increase per resistance element. The R^2 value of 0.939 shows a 93.9% adherence to a perfectly linear relationship.

In order to determine if the increases in inhalation and exhalation resistances were statistically significant, a T-test with $p < 0.05$ was performed between the means of two groups of inhalation and exhalation resistances for 0-5 resistance elements. Based on the results of the T-test it was determined that the difference in inhalation and exhalation resistances was statistically significant.

DISCUSSION

Overall, the data indicate that the addition of external respiratory resistance increases the overall internal resistance values of respiration. Although air purifying respirators have larger resistances in the inspiratory pathway than on the exhalation side, the data we have found demonstrates that respiratory protective device exhalation resistance has a slightly greater effect on wearer exhalation resistance than does respiratory protective device inhalation resistance.

To add perspective, the values of human respiratory resistances that we measured with added external resistors are very high. If these resistance values had been encountered without added external resistance elements, then the individual exhibiting them would have probably been in an emergency situation. We have measured respiratory resistances of children and adults [Johnson et al, 2005]. Whereas children with their smaller airways have far larger respiratory resistances than do adults, even most children do not have respiratory resistances as high as those measured on adults in this study. Adults with average respiratory resistances of 5.9 cm H₂O·sec/L are at the 99th percentile of expected resistances [Johnson et al, 2005]. Five added external resistances induced internal respiratory resistances almost twice as high as that.

The APD measures total respiratory resistance, including components of airway, lung tissue, and chest wall resistances. Any or all of these components could have been the cause of the respiratory system resistance increases measured. It can be speculated that airway calibre changed as external

resistance was added, but it is just as easy to imagine that the chest wall muscles may have tightened when external resistances were added, leading to higher respiratory system resistances.

This study specifically looked at the respiratory effects of the resistances that respiratory protective devices could impose upon their wearers. Many respirators also add considerable dead volume to the breathing circuit of the wearer, also of the same order of magnitude as that naturally present in the respiratory system. Dead volume accumulates carbon dioxide, and this may lead to physiological adjustments to airway calibre that may or may not counter the effects of external resistances added to the respiratory system [Johnson et al, 2000; Johnson, 2016].

There are potential sources of discrepancy that could have skewed the data. Three participants expressed potential congestion due to seasonal allergies. This could have led to somewhat altered respiratory resistance values. There was an overall consensus between all the participants that as the study went on, and more external resistance elements were being added onto the APD, breathing into the APD was growing cumbersome. This suggests that a longer adjustment period may have been necessary to ensure that the participant had plenty of time to recover and normalize their breathing before measurements were taken. It may have been better for the adjustment period to be changed to 2 minutes. The randomization of the adding of external resistance elements probably eliminated the potential for the lungs to compensate for the addition of external resistance elements and skewing the results. The results of this experiment highlight that the addition of external resistance elements has a noticeable increase on internal respiratory system resistance.

Responses measured as external resistances were added to the breathing circuit were nearly, although apparently not exactly, linear. The R^2 value, or the coefficient of determination, shows the proportion of the variance from a perfectly linear relationship. An R^2 value of 1.0 indicates that the data is perfectly linear whereas a value of 0.0 indicates that the data is not close at all to the line of regression. The R^2 values of the average inhalation and average exhalation resistance, 0.939 and 0.949 respectively, show an almost perfectly linear relationship between increasing resistance and increasing numbers of resistance elements, each 1 cm H₂O·sec/L, attached to the APD.

While no other studies have been found that performed a similar study using the same equipment, previous studies done with anaesthetic facemasks on the effect of external resistance on internal respiratory resistance state that as a result of the muscular effort of inspiration occurring more quickly than that of expiration, the pressure gradient during inspiration will be greater than that of expiration [Smith, 1961]. This is in contradiction with the results of this study, while the inhalation and exhalation respiratory system resistance values both increased with the addition of external resistance elements, the exhalation resistance increased at a slightly greater rate than that of inhalation resistance. This contradiction could be explained by the difference in the geometry of the anaesthesia masks and the position of its external resistance. In addition to this, the expected effect of external resistance on internal respiratory system resistance is that inhalation resistance would increase, but due to the change in pressure gradient, exhalation resistance would go down. This would be due to the change in the pressure gradient in the respiratory tract that occurs as a result of external added resistance. The results of the study however show that both inhalation and exhalation respiratory system resistances increase nearly linearly with the addition of external resistance elements. This could be explained by a variety of factors both physiological and technological.

The conclusions of this study could be utilized by regulators of respiratory protective devices, physicians, and scientists to characterize lung physiology under additional external resistance. Knowing that the addition of external resistance elements increases internal respiratory system resistance is vital when creating respiratory protective masks for patients with decreased lung performance due to factors such as disease and smoking [Kaminsky, 2012; Ochs and Obrodovich, 2012], and it may be important for medical surveillance of workers who may not be able to tolerate the burdens incurred when wearing respiratory protective devices.

As for respirator designers and manufacturers, knowing that respirator resistance can increase resistance inside the wearer, although probably not directly a factor in respirator design, does, at least, help to understand the physiological effects imposed on the wearer of respiratory protective equipment. The wearer should not be forgotten when respiratory protective devices are conceived. A recent study was conducted to evaluate the impact of the gas mask on indexes of respiratory effort and breathing patterns in a human model because no data exist (Bourassa et al., 2018). The authors demonstrated a substantial increase in the indices of respiratory effort both at rest and during exercise with a gas mask.

CONCLUSIONS

Respiratory protective device inhalation and exhalation resistances cause increases in respiratory system resistances of the wearer.

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