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Comparison of ISO work of breathing and NIOSH breathing resistance measurements for air-purifying respirators

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Abstract

The National Institute for Occupational Safety and Health's methods and requirements for air-purifying respirator breathing resistance in 42 CFR Part 84 do not include work of breathing. The International Organization for Standardization Technical Committee 94, Subcommittee 15 utilized work of breathing to evaluate airflow resistance for all classes of respiratory protective devices as part of their development of performance standards regarding respiratory protective devices. The objectives of this study were: (1) to evaluate the relationship between the International Organization for Standardization's work of breathing measurements and the National Institute for Occupational Safety and Health's breathing resistance test results; (2) to provide scientific bases for standard development organizations to decide if work of breathing should be adopted; and (3) to establish regression equations for manufacturers and test laboratories to estimate work of breathing measurements using breathing resistance data. A total of 43 respirators were tested for work of breathing at minute ventilation rates of 10, 35, 65, 105, and 135 liters per minute. Breathing resistance obtained at a constant flow rate of 85 liters per minute per National Institute of Occupational Safety and Health protocol was correlated to each of the parameters (total work of breathing, inhalation, and exhalation) obtained from the work of breathing tests. The ratio of work of breathing exhalation to work of breathing inhalation for all air-purifying respirators is similar to the ratio of exhalation to inhalation resistance when tested individually. The ratios were about 0.8 for filtering facepiece respirators, 0.5 for half-masks, and 0.25 for full-facepiece respirators. The National Institute for Occupational Safety and Health's breathing resistance is close to work of breathing's minute ventilation of 35 liters per minute, which represents the common walking/working pace in most workplaces. The work of breathing and the National Institute of Occupational Safety and Health's breathing resistance were found to be strongly and positively correlated (r values of 0.7–0.9) at each work rate for inhalation and exhalation. In addition, linear and multiple regression models (R-squared values of 0.5–0.8) were also established to estimate work of breathing using breathing resistance. Work of breathing was correlated higher to breathing resistance for full-facepiece and half-mask elastomeric respirators

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than filtering facepiece respirators for inhalation. For exhalation, filtering facepiece respirators were correlated much better than full-facepiece and half-mask elastomeric respirators. Therefore, the National Institute for Occupational Safety and Health's breathing resistance may reasonably be used to predict work of breathing for air-purifying respirators. The results could also be used by manufacturers for product development and evaluation.

Keywords

Correlation coefficient; exhalation; inhalation; prediction model; respiratory protective device (RPD)

Introduction

National Institute for Occupational Safety and Health (NIOSH) approval testing of air-purifying respirators (APRs) is performed using constant airflow methods, which uses two separate tests to determine the inhalation and exhalation resistances independently. These tests use continuous airflow at a steady rate of 85 l/min to determine airflow resistance. The standard test procedures (STPs) currently used for testing respirators with this method ensure these respirators meet the minimum inhalation and exhalation resistance requirements set forth in 42 CFR Part 84.

In contrast to constant flow, the work of breathing (WOB) method uses a dynamic airflow and continuously measures the inhalation and exhalation pressures. By using dynamic measurements over the current constant airflow methods, the full breath cycle is measured instead of just a single flow rate, allowing for a more complete understanding of how the respirator functions during use. Dynamic and non-linear flow effects contribute to airflow resistance, which for the latter is significant at high work rates. Such contributions are readily seen in WOB (Shykoff and Warkander 2011) where constant flow resistance measurements are limited. WOB is the energy expended to inhale and exhale a breathing gas. It is usually expressed as work per unit volume, for example, joules/liter, or as a work rate (power), such as joules/min. For this study, WOB was expressed in kPa as WOB/V_T, the power per minute ventilation. The first WOB and related parameters have been used to evaluate underwater breathing apparatuses since the 1970s (Warkander et al. 1992). In 2013, ISO proposed WOB, elastance, peak pressures, and the designation and evaluation of a work rate class as metrics for respiratory protective devices (RPDs). This effort provided a standardized methodology for the evaluation of all classes of RPDs. In the ISO method 16900, a breathing machine moves air through a respirator appropriately donned on a headform. WOB for RPDs is obtained by integrating P, pressure, measured at the respiratory inlet throughout the breathing volume (i.e., $\int PdV$).

The comparison between International Organization for Standardization (ISO) WOB and NIOSH breathing resistance has not been studied due to its recent introduction. Therefore, the main objective of this study was to evaluate the relationship between ISO WOB measurements at each of the specified work rates and NIOSH breathing resistance test results, provide a scientific basis for standards development organizations (SDO) to decide if WOB should be adopted, and establish linear and multiple linear regression equations for manufacturers and test laboratories to estimate WOB measurements using breathing resistance data.

Materials and methods

Respiratory protective devices

A total of 43 APR was tested. Table 1 shows the number of tests per respiratory protective device type and abbreviations for each class. These APR were chosen based on current availability, with an emphasis on obtaining a wide variety of filtering facepiece respirators (FFRs).

Breathing machine and headforms

The WOB test setup was configured based on ISO standard 16900-5 (ISO 2016a). A Warwick Technology dynamic digital breathing machine (Warwick Technology, Warwickshire, United Kingdom) (Figure 1) was used to simulate human breathing (Warwick Technology 2013). The breathing machine is controlled by software written in LabVIEW (National Instruments, Austin, TX). A stepper motor (N2 series servo motor, Kollmorgen, Radford, VA) moves an aluminum piston inside a cylinder to simulate changing lung volumes, with a potentiometer inside the stepper motor used to measure piston position. Due to issues that arose with the potentiometer, a position sensor using laser triangulation (Acuity AR700, Schmitt Measurement Systems, Portland, OR) was later added to the breathing machine to corroborate the potentiometer’s data. A Validyne (model CD23, Validyne Engineering, Northridge, CA) controller and pressure transducer provides the pressure measurements.

In these tests, a medium headform, based on ISO 16900-5 (ISO 2016a), was used for the testing of all respirators; see Figure 1. The ABS plastic headform was created by a 3-D printer using CAD files based on dimensions in ISO 16900-5:2016. Inside the headform, a metal tube acting as the trachea connected the mouth to the breathing machine via the neck. Since limited respiratory interfaces or coverings were used, the ISO standardized torso was not necessary for the tests performed, so a small stand was used to support the headform. The height was set so that the tube attaching the trachea to the breathing machine was not kinked or bent in a way that would create substantial additional resistance. Due to the nature/method of 3-D printing, all headforms created this way were found to be not only too rough to create a proper seal with a respirator, but they were also porous, which did not allow an airtight seal to form between the respirator and headform. To address these issues, the headforms were sanded slightly and a polyurethane sealant (Minwax fast-drying polyurethane) was applied to the outer surface of headform. Since testing the respirators required an airtight seal, duct tape was used to seal the respirator to the headform for FFRs, and Play-Doh modeling putty was used to seal elastomeric half-mask respirators (EHMRs) and full-facepiece respirators.

Waveforms

ISO 16900:12 outlines eight breathing rates based on tidal volume (L) and breathing frequency (breathing cycles/min) (10, 20, 35, 50, 65, 85, 105, and 135 l/min). These specified breathing rates were used to create sinusoidal waveform files (ISO 2016b). For the purposes of our study, WOB was calculated across only the five breathing rates ISO has specified as defined work rates (10, 35, 65, 105, and 135 l/min).

WOB test procedure

WOB methods followed ISO Standards 16900-5 and 16900-12. The test procedure, data treatment, and calculations were based on the ISO test standard 16900-12. The quantities were calculated for the five ISO work rates: resting, dynamic sinusoidal at 10 l/min; W1 flow rate, 35 l/min; W2 flow rate, 65 l/min; W3 flow rate, 105 l/min; and W4 flow rate, 135 l/min. RPD pressure and volume data were recorded for all eight ISO waveforms run in order of increasing minute volume with a 1-min duration for each waveform. RPD were not pre-conditioned prior to testing, and all WOB tests were recorded at ambient conditions. Retesting was performed if the respirator seal was found to be leaking. For more information regarding the WOB methods development see King et al. (2017).

WOB calculations

Pressure-volume (PV) data used in WOB calculations was obtained from recorded results by averaging over ten consecutive breaths at each recorded point throughout the period (O'Haver 2008). Volume data were derived from laser position sensor recordings. A more thorough discussion for calculation of volume-averaged total work of breathing normalized by the tidal volume (WOB_T/V_T), inspiratory work of breathing (WOB_{in}), and expiratory work of breathing (WOB_{ex}) can be found in Annex B of ISO 16900-12:2016 (ISO 2016b). Calculations were initially performed in Microsoft Excel 2016 and in LabVIEW (National Instruments, Austin, TX) for incorporation into the data-acquisition function. Results from LabVIEW were verified against those from the spread-sheet calculations (King et al. 2017).

NIOSH breathing resistance test procedure

The static flow resistance test consisted of two separate tests: an inhalation resistance test reflecting NIOSH STP TEB-APR-STP-0007 (NIOSH 2019a), and an exhalation resistance test reflecting NIOSH STP TEB-APR-STP-0003 (NIOSH 2019b). The two test setups were identical, with the exception that the inhalation resistance test is attached to an in-building vacuum system, while the exhalation test is connected to an in-building air compressor. The test setup for inhalation resistance, without the respirator, is shown in Figure 2. This process required respirators have an airtight seal, and therefore to be sealed to the headform with putty or wax. Putty was used for these tests. Airflow, controlled by a mass flow controller (Brooks Instrument Co., Model 5853S), is passed through the respirator at a constant rate of 85 l/min while the resistance in mm H2O is measured using a digital manometer (Setra Datum 2000, Model 239, Setra Systems Inc., Boxborough, MA).

Breathing resistance for inhalation and exhalation obtained from NIOSH breathing resistance test method was correlated to each of the parameters obtained from the ISO WOB test (WOB (total, inhalation, and exhalation), peak pressures (inhalation, exhalation), and elastance) for corresponding respirator models.

Results and discussion

The degree of correlation between the two methods can be determined by comparing current NIOSH STP results to WOB test results for all varieties of air purifying respirators. Figure 3 shows the mean WOB/V_T and NIOSH breathing resistance for inhalation and exhalation for all APRs. Each of the APR breathing resistance test results for each individual APR tested in this study met the NIOSH breathing resistance requirements (42 CFR PART 84). From Figure 3, NIOSH breathing resistance is demonstrated to be close to the WOB work rate W1, which is similar to a common walking/working pace in most workplaces. For work rate 2 (W2) and above, the average pressures derived from WOB measurements were roughly 2–5 times larger than NIOSH breathing resistance measurement results at 85 l/min. From Figure 3, the mean breathing resistance measurements for work rate at resting, W1 and W2 are in general close to the NIOSH limits and the corresponding WOB measurements are much smaller than the WOB limits. For exhalation, NIOSH breathing resistance have tighter tolerances than proposed ISO WOB for low to moderate work rates. All APRs (100%) at work rate W1 (minute ventilation 35 l/min) and 93% at work rate W2 (minute ventilation 65 l/min) met proposed WOB maximum flow rate limits for each of the work rate classifications limits. Maximum flow rates for each work rate are 0.52, 1.83, 3.4, 5.49, and 7.09 (10^{-3} m^3/s), respectively.

Comparison of WOB to NIOSH breathing resistance by RPD classes

Figure 4 shows a comparison of mean WOB/V_T with breathing resistance by RPD classes at different work rates. The mean WOB/V_T of the full-facepiece respirators was generally much higher than half-mask elastomeric and FFR for inhalation and exhalation at all work rates. The same trend was observed with NIOSH breathing resistance. Each Pair Student's t-test and All Pairs Tukey-Kramer test were used to compare mean WOB/V_T and breathing resistance for FFR, half-mask elastomeric, and full-facepiece respirators at different work rates. The test results showed a significant difference of WOB_{in}/V_T and inhalation resistance among the three RPD classes at different workflow rates at resting, W1, W2, W3, and W4. For exhalation, no significant differences of WOB_{ex}/V_T and exhalation resistance among these RPDs at low and moderate work rates at resting, W1, and W2 were found; and no significant difference was found for WOB_{ex}/V_T and exhalation resistance between half-mask elastomeric and full-facepiece respirators, whereas for FFRs a significant difference was found with half-mask elastomeric and full-facepiece respirator at work rates W3 and W4 (the high work rates).

From Figure 4, it was also found the mean WOB/V_T for full-facepiece exceeded the ISO WOB limits for high work rates W3 and W4 (see Table 3), but for the low work rates (at resting, W1 and W2), the mean WOB/V_T met the ISO WOB limit.

Table 2 summarizes the ratio of exhalation to inhalation for breathing resistance and WOB by classes. The ratio of WOB exhalation to inhalation for all APR was similar to the ratio of exhalation to inhalation resistance. The ratios were about 0.8 for FFRs, 0.5 for half-masks, and 0.25 for full-facepiece respirators. The mean of exhalation for all RPD WOB except at resting is around half of inhalation. The ratios were slightly smaller than 1 for FFRs because 5 of the 18 FFRs had an exhalation valve. For FFRs, inhalation and exhalation air both pass the filtering facepiece when there is no exhalation valve so inhalation and exhalation breathing resistance and WOB measurements are similar. Exhalation valves, used by elastomeric respirators and some FFRs, can decrease the exhalation resistance for respirators so equipped, as the exhaled air does not need to pass through the filtering element. The highest reduction in exhalation measurements was found with full-facepiece respirators, followed by half-masks and FFRs.

Correlation between WOB/V_T and NIOSH breathing resistance

Figures 5 and 6 show WOB/V_T at different work rates *vs.* breathing resistance at 85 l/min for all APR at inhalation and exhalation, and linear regression for inhalation and nonlinear regression for exhalation. WOB/V_T can be predicted well by NIOSH breathing resistance for inhalation, while for exhalation, the best match to WOB/V_T from NIOSH breathing resistance is at work rate W1 and W2. Most fibrous filters for particulates exhibit laminar flow characteristics at realistic breathing rates, and therefore should be expected to have a linear dependence between the flow rate and the resistance, with the linear coefficient depending upon the particulars of the media. As seen in Figure 5, the WOB/V_T for the different breathing rates can be well matched with linear fits, with the slopes increasing with increasing breathing rate. Similarly, Figure 7 shows the linear dependence of the fitted coefficients from Figure 5 with the flow rates for the different work rates, suggesting that WOB/V_T is proportional to the work rates tested.

The Pearson correlation coefficient r was used as a measure of the strength and the direction of the relationship between the two variables. The coefficient r approaches unity when the two variables are positively and linearly correlated. The P value expresses the significance of the relationship between two variables. Table 3 shows the calculated value of correlation coefficient and P value between WOB/V_T and breathing resistance at different work rates for inhalation and exhalation. Most correlation coefficients between WOB/V_T and breathing resistance were above 0.7, indicating that they were strongly correlated except at resting (r = 0.24) for inhalation and (r = 0.29) for exhalation. P-values were low, below 0.0001 except for inhalation at rest with a P-value of 0.127, due to the variation between respirator types. Table 3 also showed correlation coefficient R between WOB/V_T and breathing resistance at different work rates for inhalation and exhalation by classes of respirators. The average correlation coefficient for full-facepiece, half-mask elastomeric, and FFR are 0.79, 0.79, and 0.61 for inhalation and 0.81, 0.53, and 0.92 for exhalation, respectively. WOB/V_T correlations to breathing resistance for full-facepiece and elastomeric half-mask were better than FFR for inhalation; for exhalation, FFR was much better than full-facepiece and half-mask elastomeric.

Multiple linear regression models for WOB/V_T and NIOSH breathing resistance

To learn more about the relationship between the five waveforms and breathing resistance for inhalation and exhalation, multiple regression analysis was used to create a prediction model. The data were fairly well matched using a multiple linear fit (R^2 value = 0.88 for inhalation, from Figure 8, and R^2 value = 0.79 for exhalation, from Figure 9) but displayed a systematic deviation at higher values. Table 4 shows lack of fit for the inhalation and exhalation prediction model. Prob > F lists the P value for the lack of fit test. Both p-values were not small, indicating that the prediction models were not significant for lack of fit.

Since airflow through fibrous particulate filtration media is typically low Reynold's number, in the ideal case the instantaneous resistance is directly proportional to the instantaneous flow rate. The maximum flow rate for Work Rate W4 (ISO 16900-12:2016) is

$$F_{\mathrm{Max}} = \frac{\pi}{\tau} V_T = 7.25 \times 10^{-3} \mathrm{m}^3 \cdot \mathrm{s}^{-1}$$

where **τ** is the period of the breath and V_T is the tidal volume. A maximum inhalation resistance $R_{85 \mathrm{l/min l/min}}$ of 343 Pa (35 mm H_2O) at 1.42 10^{-3} m^3 s^{-1} (85 l/min), the NIOSH limit for non-powered air-purifying particulate respirators, would ideally correspond to a maximum resistance of 1760 Pa at this F_{Max}, some-what below the ISO limit of 2000 Pa. If one assumes a linear resistance coefficient,

$$\rho_l = F\_(85 \quad \mathrm{l/min}) R\_(85 \quad \mathrm{l/min})$$

the value associated with the NIOSH limit would be

$$\rho_l = 4.14 \times 10^{-6} \mathrm{m}^4 \cdot \mathrm{s} \cdot \mathrm{kg}^{-1}$$

The work of breathing for one inhalation of one cycle of the ISO breath, F_{Max} sinat is

$$\mathrm{WOB}_{\mathrm{In},\ \tau} = \int_0^{0.5\tau} FP \quad dt = \int_0^{0.5\tau} \frac{1}{\rho_l} F_{\max}^2 \sin^2 at dt$$
$$= \frac{\tau}{4\rho_l} F_{\max}^2,$$

or 4.13 J/(1.3 s), 3.17 W. WOB/V_T = 1:375kPa, some-what less than the ISO limit of 1.6 kPa. These calculations depend upon the idealized linearity of the filter resistance, and deviations are likely to lead to higher resistances at higher flow rates. Exhalation resistance for respirators with exhalation valves can be assumed to be strongly nonlinear, and these calculations would not apply. For exhalation with respirators with no valve the analysis is similar.

Conclusions

The above analysis and discussion allow the following conclusions to be drawn.

1. NIOSH breathing resistance was strongly and positively correlated with WOB. Linear and multiple linear regression models (R-squared values of 0.5–0.9) were established to estimate WOB using breathing resistance.

2. Manufacturers and test laboratories can estimate WOB by using breathing resistance data for selected respirators.

3. WOB was better correlated to breathing resistance for full-facepiece and half-mask elastomeric respirators than FFRs for inhalation; for exhalation, FFRs had better correlation to WOB than full-facepiece and half-mask elastomeric respirators; the average WOB for full-facepiece was significantly higher than for half-mask elastomeric respirators and FFRs for both inhalation and exhalation.

4. The ratio of exhalation WOB to inhalation for all APRs is similar to the ratio of exhalation to inhalation resistance. The ratios were about 0.8 for FFRs, 0.5 for half-masks, and 0.25 for full-facepiece respirators.

5. Statistical analysis showed that there was a significant difference of WOB_{in}/V_T and inhalation resistance among three RPDs at different work rates at resting, W1, W2, W3, and W4. For exhalation, there was no significant difference found for WOB_{ex}/V_T and exhalation resistance among three RPDs at low and moderate work rates at resting, W1, and W2; and there was no significant difference found for WOB_{ex}/V_T and exhalation resistance between half-mask elastomeric and full-facepiece respirators, whereas FFRs were significantly different with half-mask elastomeric and full-facepiece respirators at work rates W3 and W4 (which are high work rates).

Potential use of study findings and study limitations

Currently, respirators undergo a specific set of approval testing procedures based on the type of respirator and the desired outcome (e.g., determination of breathing resistance, determination of exhalation valve leakage, and maintenance of positive pressure). All respirators must meet a minimum inhalation and exhalation resistance requirement set forth in 42 CFR Part 84.

This study examines the correlation between the test results from current set of NIOSH test methods and the test results for newly proposed ISO WOB method. How the methods compare may provide a basis on which better decisions can be made by NIOSH or other standard development organizations and suggests NIOSH requirements remain relevant even as international standards are updated. Additionally, the test equipment needed to execute the NIOSH test procedures for inhalation and exhalation resistance are relatively simple and can be constructed using commercially available parts. The ISO WOB test method, by contrast, is more complex because a sinusoidal breathing machine is needed as well as the headforms described in ISO 16900-5:2016.

Manufacturers and test houses without the capability to run WOB tests can measure breathing resistance and use our regression equations to estimate WOB values. In comparison to the complex equipment required to measure WOB over full breathing cycles, equipment to determine breathing resistance at a single flow rate is very generic. Indeed, common filter efficiency testing equipment reports the breathing resistance during penetration testing (see, for example, TSI Incorporated 2019). While WOB is not a new to the respirator field, it has not traditionally been used for APRs. Manufacturers may not currently have the equipment or expertise for the ISO WOB method, and breathing resistance at a set flow rate could function as a simplified estimator of WOB. In this case, manufacturers can simply measure breathing resistance and then use the regression equations reported here to predict WOB results.

Manufacturers may use the variability for product development and evaluation. Large variability in WOB results was observed in this study, due to usual experimental variability and notably as well to the wide variety of respirator designs. The analysis in this work consciously neglects the effects of design differences, to allow predictions for the widest array of respirators. If the variability is reduced, the likelihood of false negatives in conformance testing could also be reduced. The respirators used in this study were limited to FFRs, half-mask elastomeric, full-facepiece respirators, and loose- and tight-fitting PAPRs. Other types of respirators such as supplied air respirators and self-contained breathing apparatus are not yet to be evaluated.

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Figure 1.
Breathing machine and 3D medium headform.

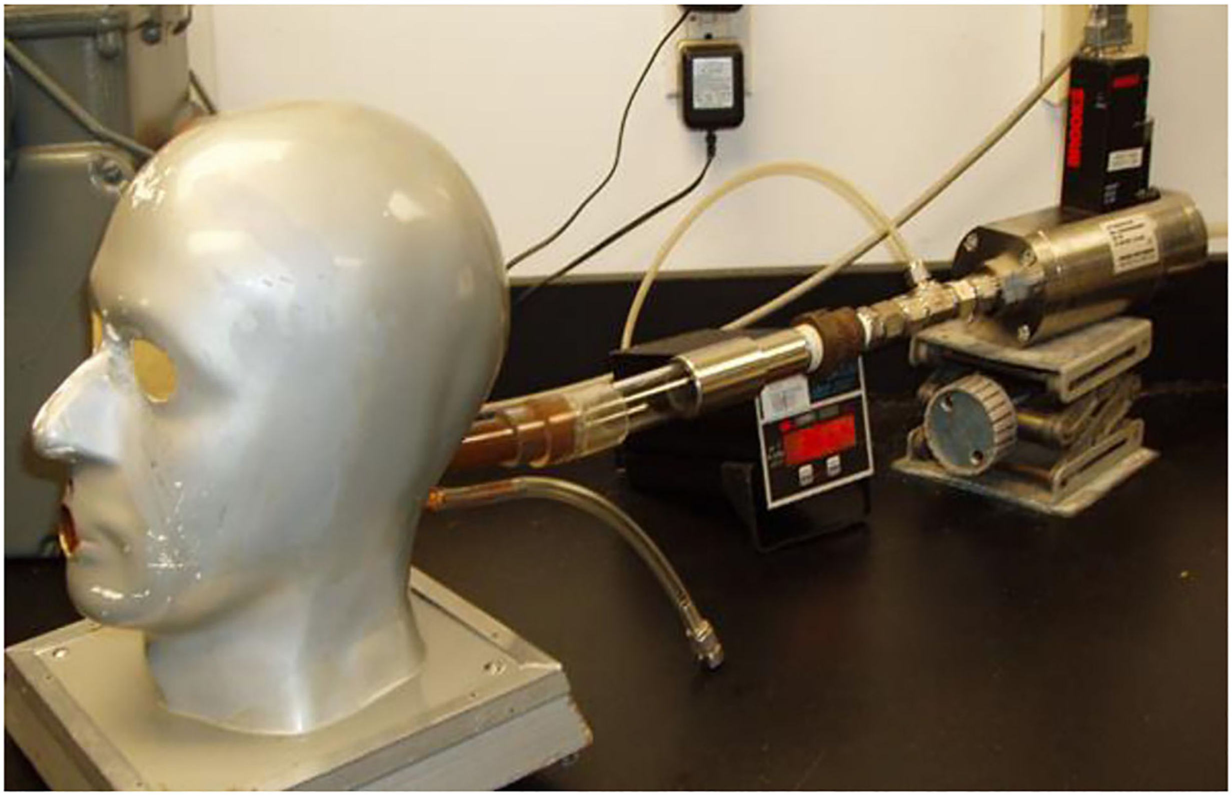

Figure 2.
Test fixture for evaluation of inhalation resistance at a constant flow rate of 85 l/min using the NIOSH Standard Test Procedure (NIOSH 2019a). The exhalation resistance fixture is a mirrored version (NIOSH 2019b).

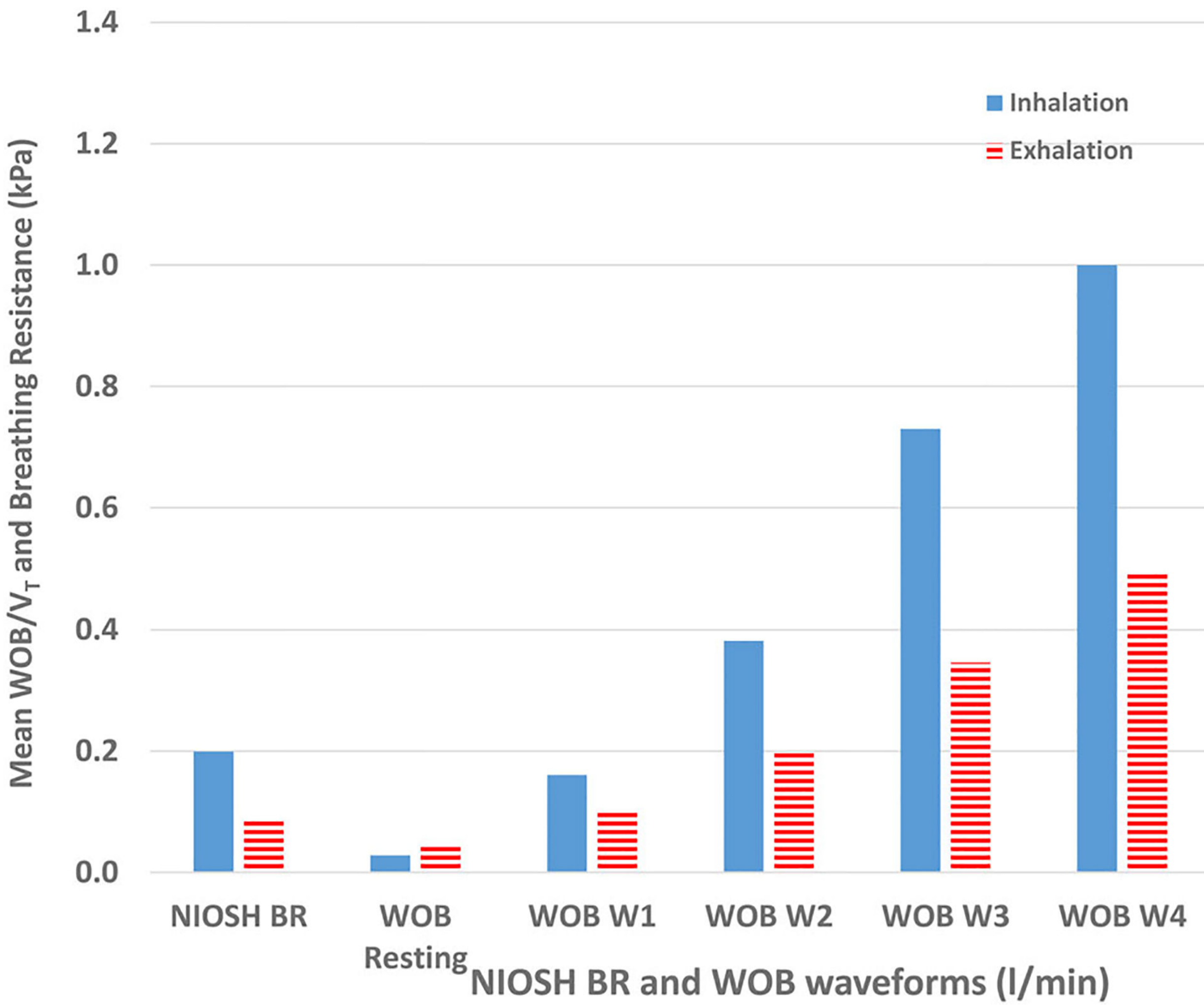

Figure 3.
Mean WOB/V_T (kPa) and NIOSH breathing resistance for inhalation and exhalation for all APRs.

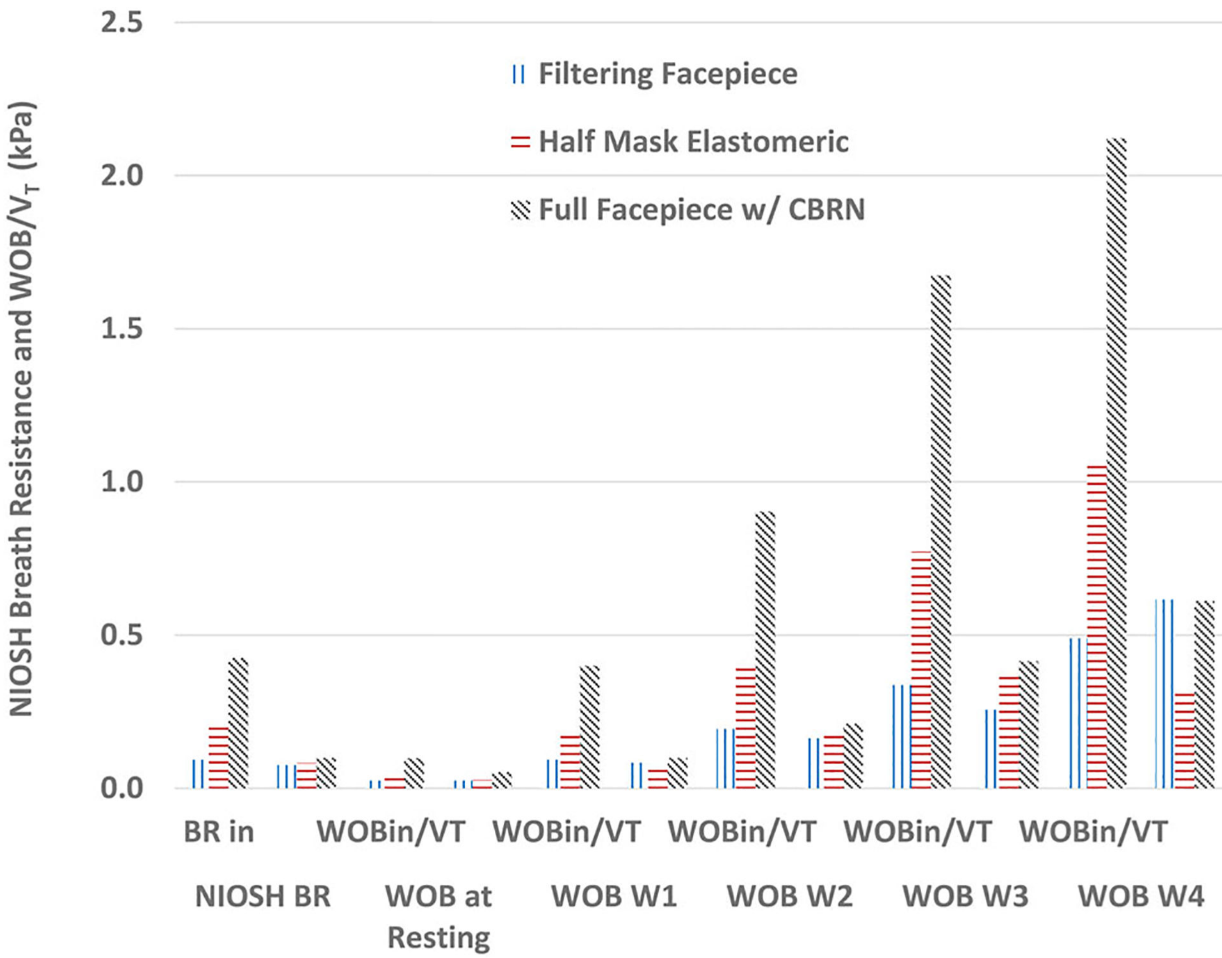

Figure 4.

Comparison of Mean WOB/V_T (kPa) with breathing resistance by RPD classes.

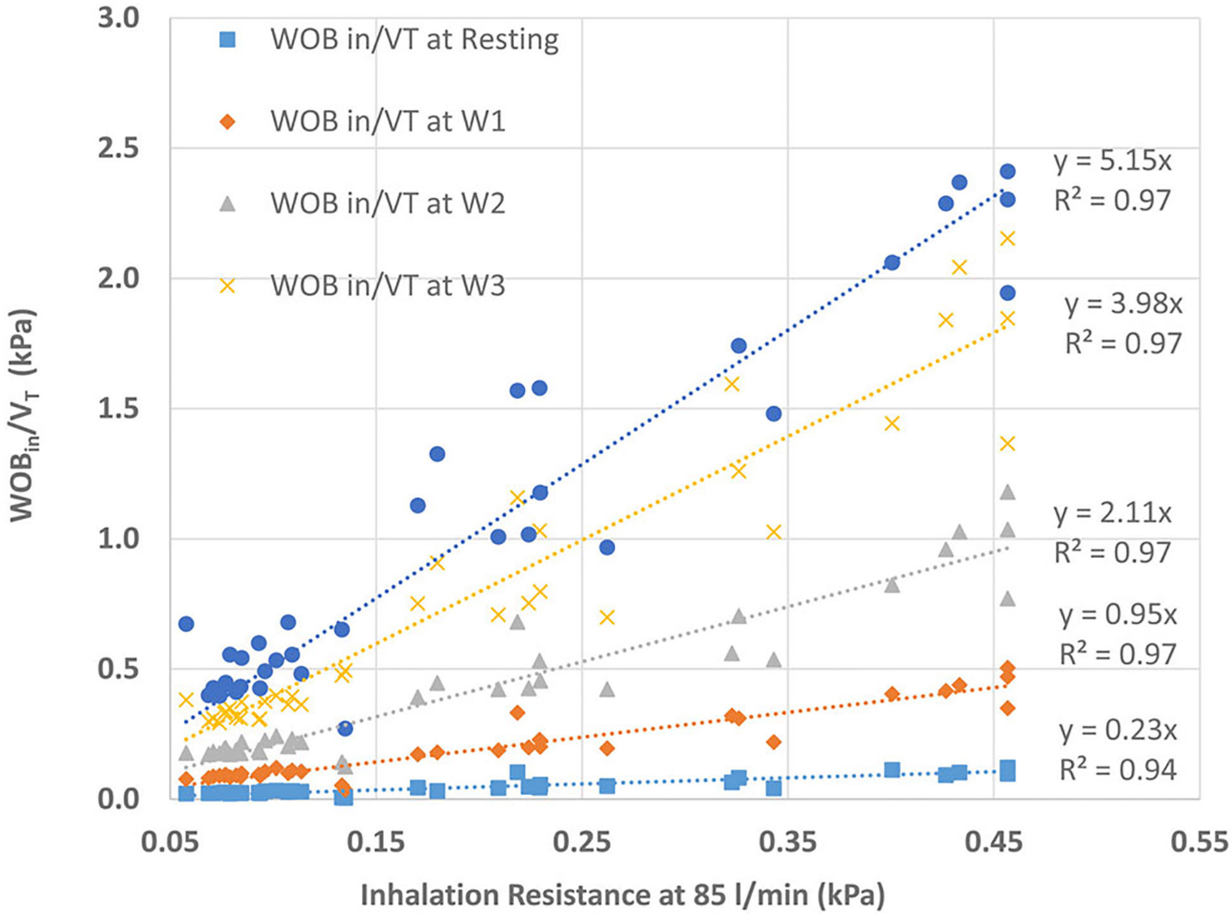

Figure 5.
WOB_{in}/V_T (kPa) vs. inhalation resistance at 85 lpm for all APR at different work rates.

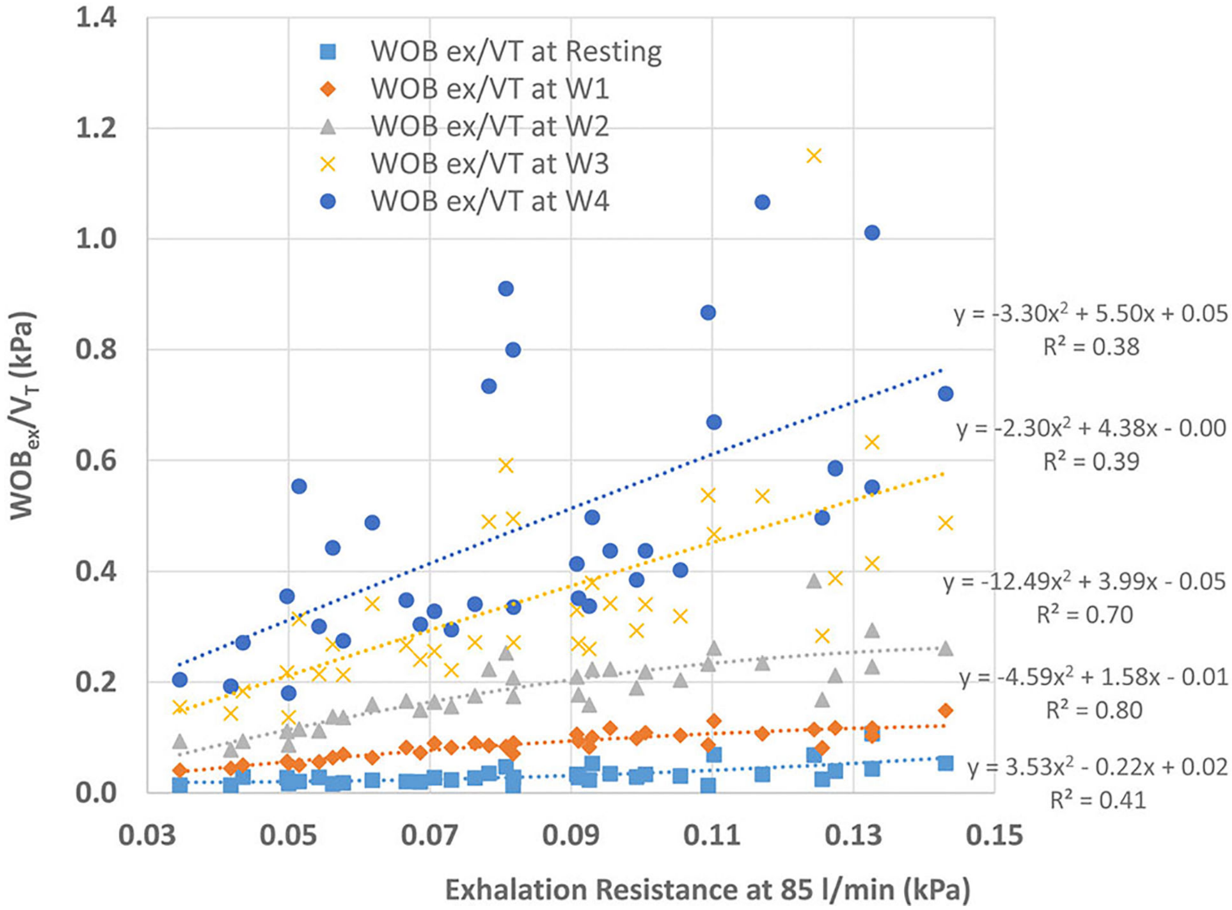

Figure 6.
WOB_{ex}/V_T (kPa) vs. exhalation resistance at 85 l/min for all APR at different work rates.

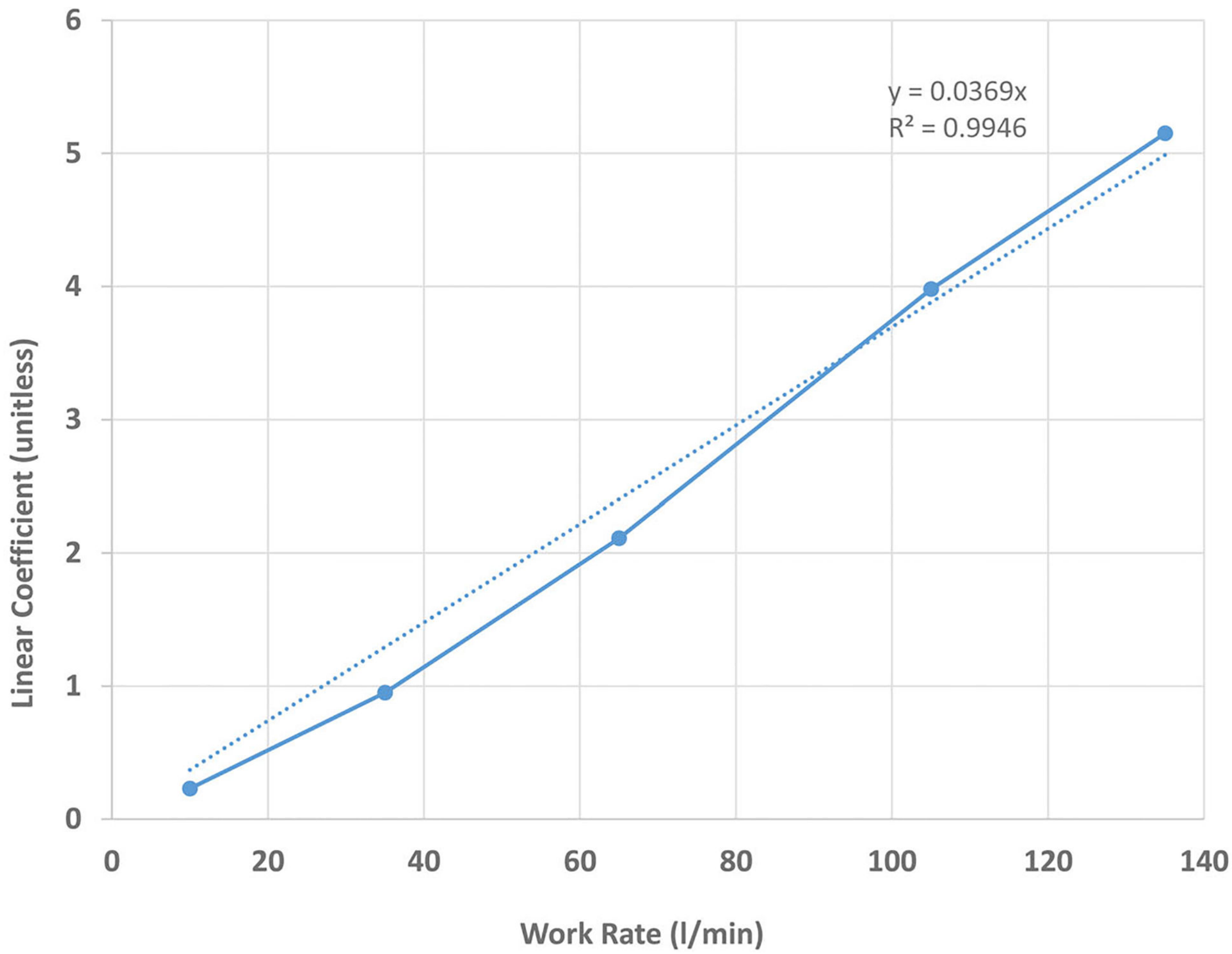

Figure 7.

Linear dependence of the fitted coefficients from Figure 5 with the flow rates for the different work rates.

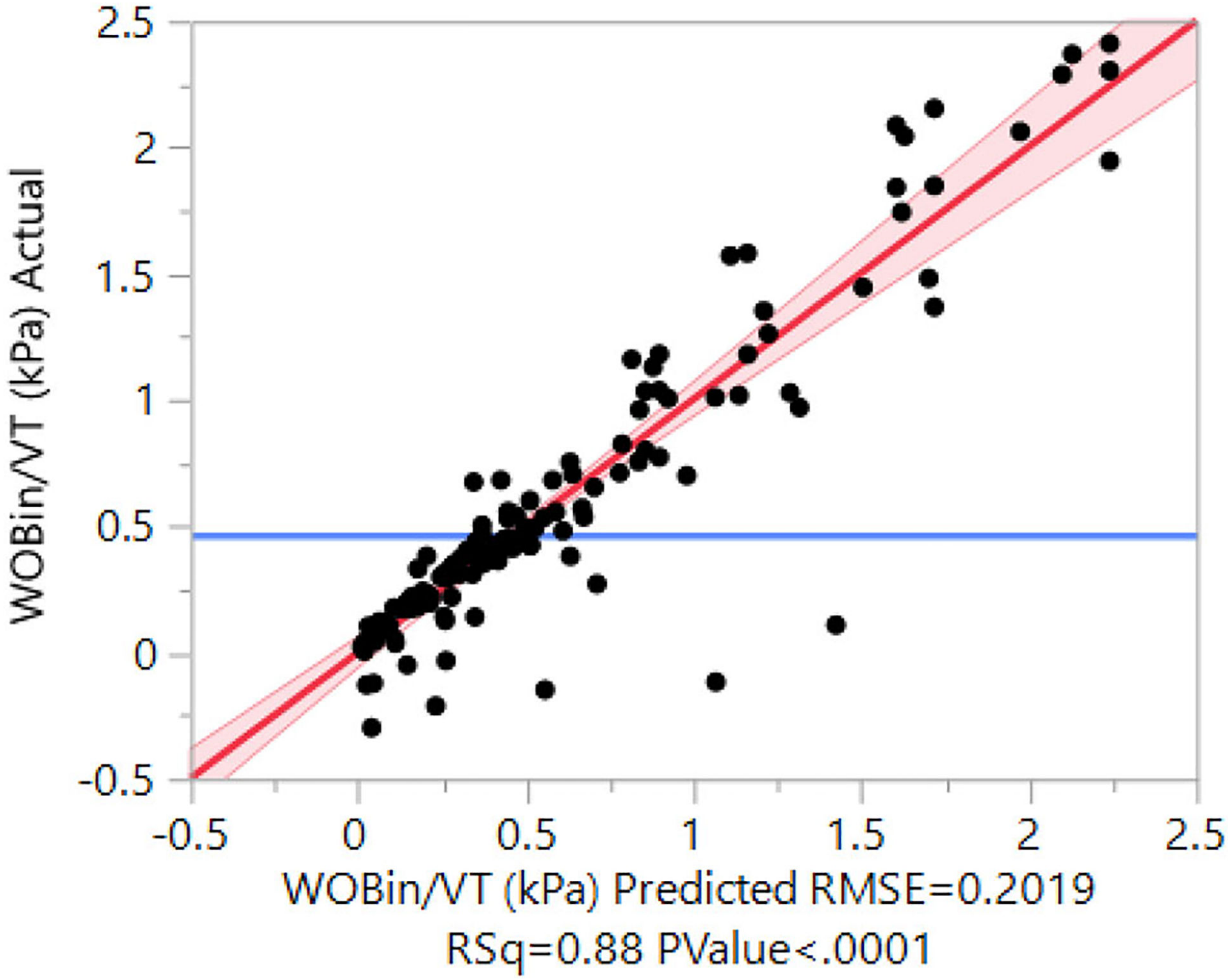

Figure 8.
Actual by predicted plot for inhalation.

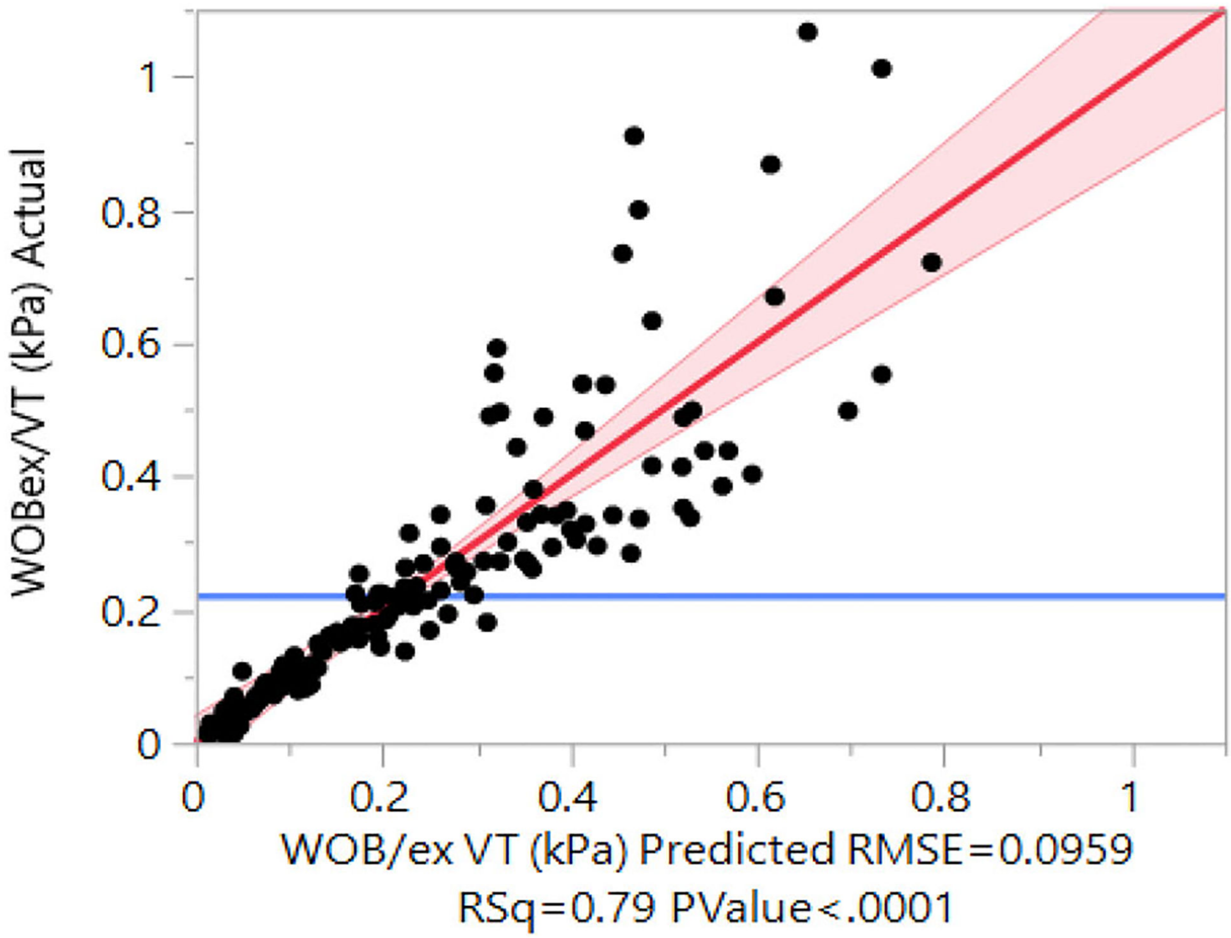

Figure 9.
Actual by predicted plot for exhalation.

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Table 1.

RPD classes, abbreviations, and test numbers for each class.

RPDs and abbreviations	Number of tests
Filtering facepiece [FFR] (N95) half-mask	17
Filtering facepiece [FFR] (P100) half-mask	1
Half-mask elastomeric respirator [EHM] (N95, P100 cartridge)	3,7
Full-facepiece elastomeric respirator [EFF] (CBRN Cap-1, P100 cartridge)	5,2
Powered air-purifying respirators [PAPR], loose-fitting (loose-fitting hood, helmet)	6
Powered air-purifying respirators [PAPR], tight-fitting respirator	2

Table 2.

Ratio of exhalation to inhalation for breathing resistance and WOB/V_T (kPa) by class.

RPD classes	Resistance	Resting	W1	W2	W3	W4
Filtering facepiece	0.81	0.98	0.90	0.84	0.76	0.67
Half-mask elastomeric	0.41	0.59	0.42	0.44	0.49	0.58
Full-facepiece w/ CBRN	0.23	0.53	0.25	0.23	0.25	0.29
All RPD (mean)	0.48	0.70	0.52	0.51	0.50	0.51

Table 3.

Correlation coefficient r and associated p-value between WOB/V_T and breathing resistance at different work rates for inhalation and exhalation by classes of respirators.

Variable	Variable	Correlation coefficient r				p-value for all classes
		Full-facepiece	Half-mask elastomeric	Filtering facepiece	All classes	
WOB_{in}/V_T Resting	Inhalation resistance	0.84	0.72	0.77	0.26	0.127
WOB_{in}/V_T W1		0.81	0.80	0.83	0.71	<0.0001
WOB_{in}/V_T W2		0.79	0.83	0.74	0.86	<0.0001
WOB_{in}/V_T W3		0.72	0.82	0.46	0.89	<0.0001
WOB_{in}/V_T W4		0.80	0.79	0.25	0.90	<0.0001
WOB_{ex}/V_T Resting	Exhalation resistance	0.66	0.17	0.91	0.79	<0.0001
WOB_{ex}/V_T W1		0.91	0.80	0.93	0.84	<0.0001
WOB_{ex}/V_T W2		0.90	0.67	0.92	0.88	<0.0001
WOB_{ex}/V_T W3		0.81	0.47	0.92	0.73	<0.0001
WOB_{ex}/V_T W4		0.74	0.54	0.92	0.59	<0.0001

Table 4.

Lack of fit sum of squares analysis for inhalation and exhalation.

	Source	DF	Sum of squares	Mean square	F ratio	p-level	Max R^2
Inhalation	Lack of Fit	165	6.60	0.04	0.75	0.78	0.99
	Pure Error	10	0.53	0.05			
	Total Error	175	7.14				
Exhalation	Lack of Fit	154	1.33	0.01	0.32	0.99	0.98
	Pure Error	5	0.13	0.03			
	Total Error	159	1.46				