Peak Inspiratory Flows of Adults Exercising at Light, Moderate and Heavy Work Loads

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ABSTRACT

The purpose of this study was to acquire, process, and analyze ventilation and peak inspiratory airflows during exercise to obtain a representative sample set of ventilation data of the general working population. A total of 13 volunteers exercised on a treadmill at three relative work rates of 40%, 60%, and 80% of their maximal aerobic capacity. Ventilation measurements and peak inspiratory airflows were recorded at each work rate for a two-minute period using an automated gas analysis system. Average ventilation results were consistent with previous research findings during equivalent workloads. As workload increased from moderate to heavy exercise the ratios of maximum and mean peak inspiratory airflow-to-minute ventilation decreased. Mean peak inspiratory airflow measurements when combined with a greater sampling frequency may provide a more accurate and robust depiction of ventilation and peak inspiratory flow during different levels of exercise.

Keywords: peak inspiratory airflow, ventilation, exercise, methodology

INTRODUCTION

Current standards used to design and evaluate respirators are based largely on minute ventilation and peak inspiratory airflow data collected more than sixty years ago by Silverman, Lee, Lee, Drinker, and Carpenter (1943). Silverman et al.'s data was collected on equipment that, by today's standards, is obsolete. Given this, one objective of this study was to collect minute ventilation and peak inspiratory airflow through the use of contemporary, standardized exercise test equipment. The underlying assumption is not that the previous data is incorrect or inadequate; rather, contemporary standards that specify criteria for the design and evaluation of respiratory protective equipment should be based upon data obtained through implementation of standardized exercise testing methods and use of commercially available professional test equipment. This study sought to expand upon and validate Silverman et al.'s findings.

Silverman et al. (1943) focused on being able "to determine the rate of airflow and the shape of the inspiratory curve in human subjects breathing with and without resistance to airflow and under varying conditions of work." He contended that the airflow values determined by Henderson and Haggard (1927) were too simplified, and that their calculations were derived from minute volume data obtained from subjects running at a slow jog, rather than at more realistic moderate-to-heavy exercise intensities that often occur when wearing a respirator. Furthermore, Silverman's group argued that Henderson and Haggard's overly simplified calculations assumed inspiratory airflow curves were rectangular in shape.

In an attempt to accurately measure inspiratory airflow and better understand the implications on the design and testing of respiratory protective equipment, Silverman's group designed their own metabolic measurement equipment. Their custom equipment enabled them to collect and analyze respiration rates, minute ventilation ($\dot{V}_E$), peak inspiratory airflows (PIF), lengths of inspiratory and expiratory cycles, and sustained rates of airflows above two-thirds of the maximum peak flow.

Kaufman and Hastings (2005) attempted to "quantify respiratory demand during operationally relevant tasks." Their research design utilized a very narrowly defined group of subjects (young, fit Marines). Ventilation data was obtained and regions of peak respiration (RPR), consisting of 10 consecutive breaths with the highest peaks were identified and analyzed. Measurements were recorded during high levels of exercise activity in an attempt to observe the effects of exercise intensity on the shape (sinusoidal, rectangular, or trapezoidal) of the ventilation waveforms.

While Silverman, et al.'s (1943) early work provided the basis for airflow rates still in use today for industrial respirator approval tests (Federal Register, 1995), it has a number of notable limitations. As stated earlier, one of the most obvious concerns with the findings presented by Silverman et al. (1943) is that they did not gather their data using standardized test equipment. The metabolic and ventilation testing equipment used today is standardized and quantifiable across the industry. Kaufman and Hastings's (2005) work utilized a widely accepted paradigm for data collection and measured subjects in relevant work environments; however, they were unable to measure oxygen consumption ($\dot{V}O_2$) during the exercises. Furthermore, both Kaufman and Hastings (2005) and Silverman et al. (1943) isolated very homogeneous and specific populations as their study samples, thereby limiting the robustness and applicability of their findings onto today's working population.

The present study, in two parts, addresses a number of the methodological limitations of the Silverman, et al. (1943) and Kaufman and Hastings's (2005) studies. This study will not examine ventilation in the presence of resistance, but rather address the baseline ventilation standards as established by the work of the Silverman and Kaufman groups. This paper will detail the standard exercise testing methodology employed in this study and present the results along with a brief discussion of the overall trends and patterns observed. Additionally, the mean and maximum values of peak inspiratory airflows and general breathing patterns in normal working adults working at light, moderate, and heavy workloads will be presented. A second paper (Janssen et al. (2005)) continues the discussion of the findings and comments on the implications of the findings with respect to respirator design and evaluation.

METHODS

Subjects

Thirteen healthy subjects (8 male, 5 female) were randomly selected from a pool of fifty-four 3M Company employee volunteers to participate in the study. For a detailed description of subject recruitments and characteristics see Janssen et al. (2005).

Protocol

Phase I. Baseline assessment of maximal aerobic capacity ($\dot{V}O_{2\,max}$)

Maximal aerobic capacity ($\dot{V}O_{2\,max}$) was determined via a maximal graded exercise test that was continued until exhaustion. Pulmonary gas exchange was measured using a CPX/D system (see Janssen et al. (2005) for a detailed description of the equipment used). A preVent mask with a silicon coupler and preVent pneumotach flowmeter was securely attached to the subject's head to provide a tight seal. Each subject's maximal graded exercise test began with a warm-up period in which subjects walked on the treadmill at a speed of 3.3 mph with a 0% grade for 3 minutes. Following warm-up, maintaining the speed at 3.3 mph, the treadmill elevation was increased 2% every 2 minutes until the subject was exhausted and/or could not continue (Bruce, 1974). For the cool down, treadmill elevation was reduced to a 0% grade and speed was lowered to each subject's preferred rate.

Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), heart rate, and respiratory exchange ratio (RER) were measured continuously. RER is the ratio of $\dot{V}CO_2$ to $\dot{V}O_2$. Blood pressure and a 12-lead electrocardiogram were recorded every 2 minutes during the test. $\dot{V}O_{2\,max}$ was considered to be attained if two of the following three criteria were achieved: 1) the subject's RER exceeded 1.1; 2) the subject's maximal heart rate exceeded 90% of his/her age-predicted maximum (220 - age); and 3) a plateau in $\dot{V}O_2$ occurred (a plateau is considered a change in $\dot{V}O_2$ of less than 0.2 L/min). If subjects did not attain two of the three criteria, but decided to stop running on his/her own volition, their $\dot{V}O_{2\,max}$ at the end of the test was used for part two of the study. The above-mentioned criterion was followed: 1) to determine when $\dot{V}O_{2\,max}$ was attained, and 2) as a precautionary measure to ensure the safety of the participants (ACSM, 2000).

Calculation of relative work effort to elicit 40%, 60%, and 80% of $\dot{V}O_{2\,max}$

Prior to phase II of the study, an estimation of the relative work effort necessary to elicit 40%, 60%, and 80% of each participant's $\dot{V}O_{2\,max}$ were determined to correspond with previously defined light, moderate, and heavy/vigorous work (Sharkey, 1977; Fox et al., 1993; ISO, 2004). For each participant, the treadmill incline corresponding to 40%, 60%, and 80% of their baseline $\dot{V}O_{2\,max}$ was used to achieve the three exercise test levels of light, moderate, and heavy work (Caretti et al., 1998; Johnson et al., 1999). See Figure 1 for an illustration of the work effort estimation technique.

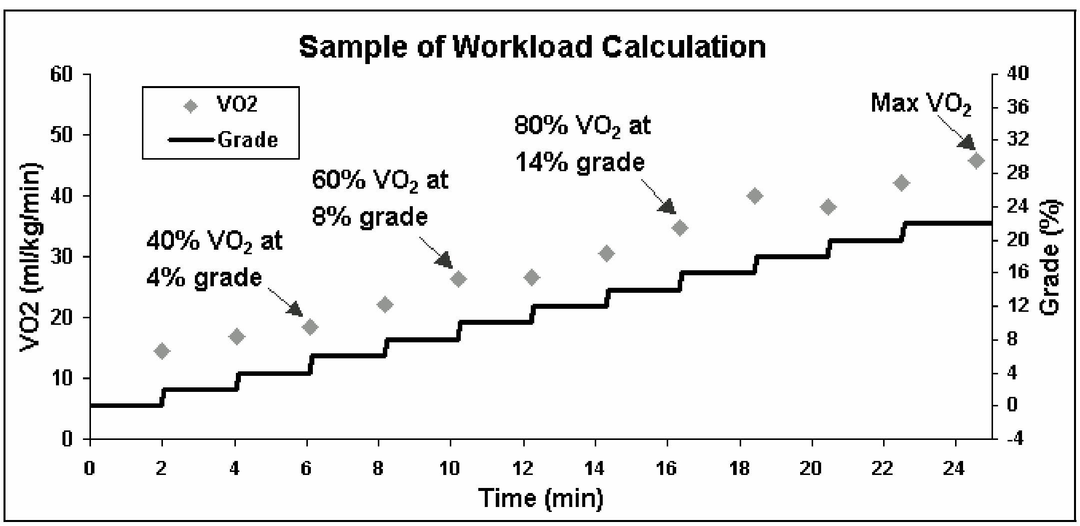


Figure 1. Illustration of the relative workload calculation based on the maximal aerobic assessment.

Phase II. Measurement of respiration and peak inspiratory airflow during exercise

Participants were instructed to report their subjective assessment of physical stress via Ratings of Perceived Exertion (RPE) using the Borg CR-10 scale (ACSM 2000). An initial warm-up period lasting 3 minutes was completed with the treadmill set at 3.3 mph and the treadmill incline set to 0% grade. To begin the 6 minute exercise test, the treadmill speed and incline were manipulated to the participant's predetermined speed and incline corresponding to approximately 40% of their $\dot{V}O_{2\,max}$. During the first 4 minutes of the light work testing period $\dot{V}O_2$ and heart rate were monitored via the Breeze Suite 6.1 software. A minimum of 4 minutes was allotted to ensure that $\dot{V}O_2$ reached a steady state (Barstow, 1994). Approximately 40% of their $\dot{V}O_{2\,max}$ was maintained for the two-minute sampling interval. At the completion of the 4-minute period participants utilized the Borg Scale to convey their RPE. The Breeze software was disabled and the customized MedGraphics DataLogger software application was enabled during the final two minutes of the light work testing period. Instantaneous inspiratory and expiratory airflows were sampled at a rate of 100 Hz.

Following the completion of the light work testing period, the treadmill speed and incline were adjusted corresponding to 60% of the participant's $\dot{V}O_{2\,max}$. The same procedure as described above was followed for 60% of $\dot{V}O_{2\,max}$ and again for 80% of $\dot{V}O_{2\,max}$. The battery of tests was completed in a period of 18 minutes. See Figure 2 for an illustration of the data collection procedure.

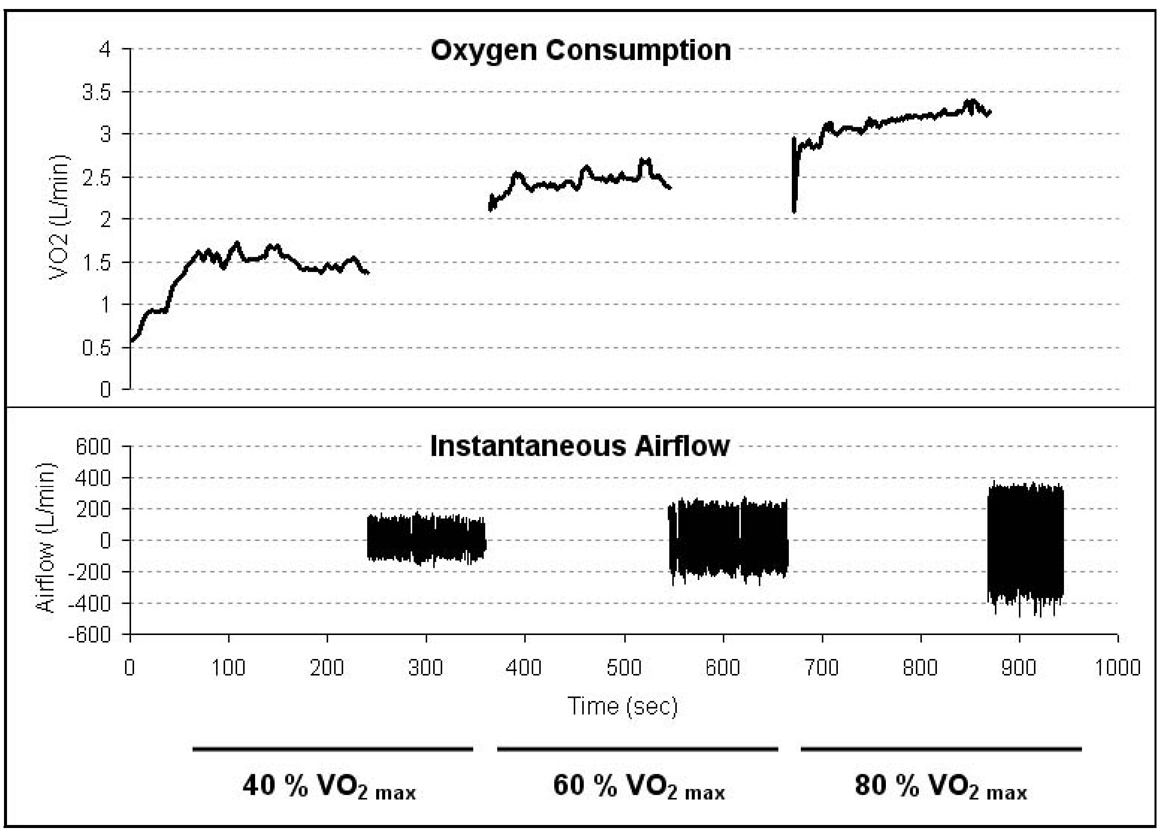


Figure 2. Illustration of data collection timeline.

Data Analysis

The following data was used to quantify the three work testing periods: RPE, HR, $\dot{V}O_2$, and metabolic equivalents (METS). METS were calculated for each workload by dividing the $\dot{V}O_2$ (ml/kg/min) at each workload by 3.5 (ACSM, 2000). The data collected during the final two-minute sample for each work testing period included: minute ventilation ($\dot{V}_E$), maximum peak inspiratory airflow (PIF_{max}), mean peak inspiratory airflow ($\overline{PIF}$), breath frequency (F), mean tidal volume ($\overline{V_t}$), mean inhalation time ($\overline{T_I}$), mean breath cycle time ($\overline{T}_{tot}$), duty cycle (DC), volume of peak flow at 5% ($V_{peak\ \pm 5\%}$), volume of peak flow at 10% ($V_{peak\ \pm 10\%}$), volume of peak flow at 25% ($V_{peak\ \pm 25\%}$). For definitions of the variables mentioned above refer to Janssen et al. (2005).

Statistics

SPSS version 13.0 (SPSS, Inc., Chicago, IL) was used to perform within subject's repeated measures analysis of variance (ANOVA) for the effect of exercise on the following ratios:

- PIF_{max}: $\dot{V}_E$ (see Figure 3)
- $\overline{PIF}$: $\dot{V}_E$ (see Figure 3)
- $V_{peak+/-5\%}$: $\overline{V_t}$ (see Figure 4)
- $V_{peak+/-10\%}$: $\overline{V_t}$ (see Figure 4)
- $V_{peak+/-25\%}$: $\overline{V_t}$ (see Figure 4)

A post hoc pairwise analysis was performed for any significant effects.

RESULTS

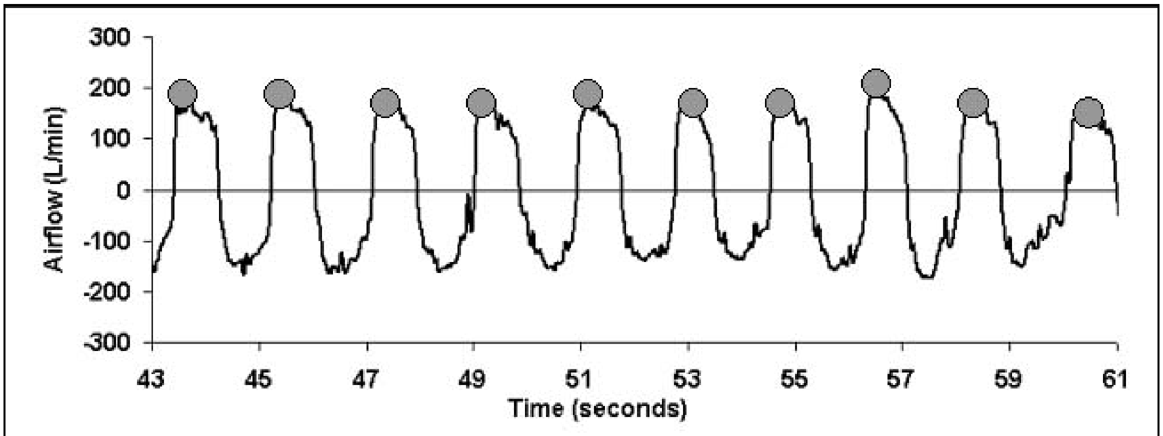
Relative work rates

Light work (Target: 40% $\dot{V}O_{2\,max}$)

All subjects performed at an average percent $\dot{V}O_{2\,max}$ of 39.6% ± 4.4. The average metabolic equivalent (METS) was 4.3 ± 0.9, which is classified as just slightly above Light-Moderate exercise intensity (Sharkey, 1977; Fox et al., 1993). The subjects' average heart rate was 99 ± 9 beats per minute (bpm), which is classified as Light-Moderate exercise intensity (Sharkey, 1977; Fox et al., 1993). The average rating of perceived exertion (RPE) was 2 ± 1, corresponding to a rating of between “very light” and “light” on the perceived rating scale. The average workload was a walking speed of 3.3 mph at 1.5% grade for all subjects.

Moderate work (Target: 60% $\dot{V}O_{2\,max}$)

All subjects performed at an average percent $\dot{V}O_{2\,max}$ of 61.5% ±5.9. The average METS was 6.5 ± 1.5, which is classified as Moderate-Heavy exercise intensity (Sharkey, 1977; Fox et al., 1993). The subjects' average heart rate was 122 bpm ± 13, which is classified as Moderate-Heavy exercise intensity (Sharkey, 1977; Fox et al., 1993). The average RPE was 3 ± 1, corresponding to a rating of between “moderate” and “somewhat hard” on the perceived rating scale. The average walking speed for all subjects was 3.3 mph at 7.0 % grade.



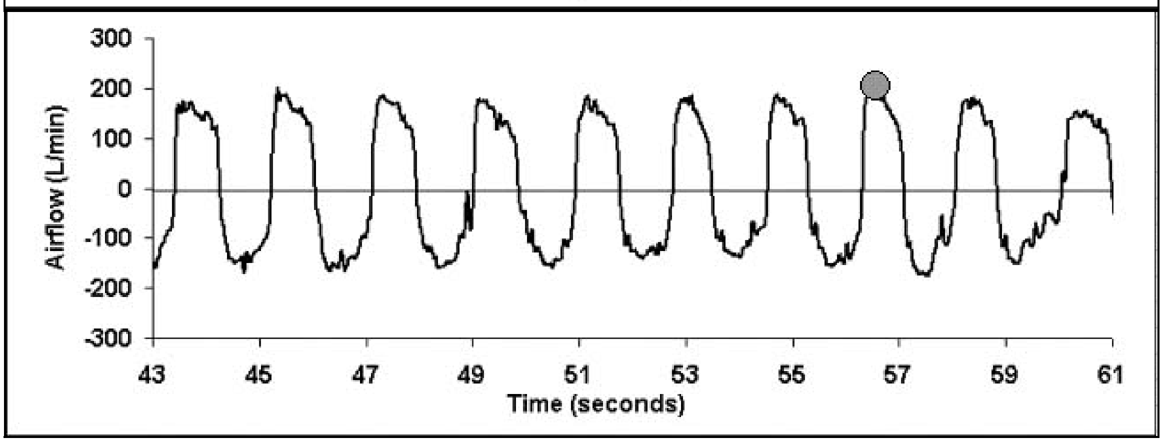


Figure 3. Illustration of the difference between PIF_{max} (top) and $\overline{PIF}$ (bottom). The gray dots represent peak inspiratory airflow for the entire sample (top) and for each individual breath (bottom).

Heavy work (Target: 80% $\dot{V}O_{2\,max}$)

All subjects performed at an average percent $\dot{V}O_{2\,max}$ of 80.9% ± 5.3. The average METS was 8.6 ± 1.7, which is classified as Heavy-Severe exercise intensity (Sharkey, 1977; Fox et al., 1993). The subjects' average heart rate was 150 bpm ± 15, which is classified as Moderate-Heavy exercise intensity (Sharkey, 1977; Fox et al., 1993). The average RPE was 5 ± 2, corresponding to a rating of "heavy" on the perceived rating scale. The average walking speed for all subjects was 3.3 mph at 12.5 % grade.

Ventilation data

Table I provides descriptive statistics of the means ±SD of the ventilation results. The average number of breaths analyzed per subject for each workload was: 42 ±11, 50 ±14, 62 ±17 for light, moderate, and heavy workloads respectively. The expected generalized trends from 40% to 60% and from 60% to 80% were observed in each of the collected variables.

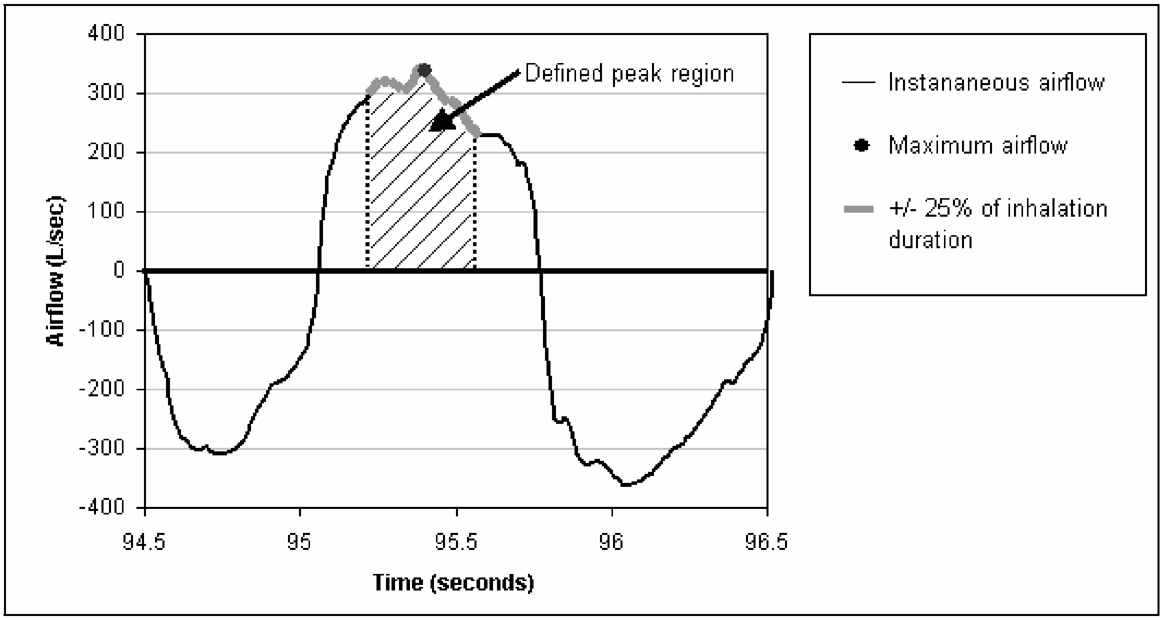


Figure 4. Defined-peak of +/- 25% of inhalation duration.

Table I. Summary of Ventilation Results ($\overline{\mathrm{PIF}}$ and PIF_{max} are measures of instantaneous airflow and should not be considered average flow.)

Variables (Units)	**Light Work Mean (SD)**	**Moderate Work Mean (SD)**	**Heavy Work Mean (SD)**
$\dot{V}_E$ (L/min)	30.3 (6.2)	47.4 (13.5)	72.3 (22.9)
$\overline{\mathrm{PIF}}$ (L/min)	100.3 (18.9)	150.1 (35.4)	218.4 (53.7)
PIF_{max} (L/min)	125.6 (29.2)	185.3 (37.1)	254.7 (57.8)
F (Breaths/min)	21.9 (5.3)	26.5 (6.7)	31.9 (7.4)
$\overline{V_t}$ (L)	1.45 (0.40)	1.86 (0.53)	2.30 (0.58)
$\overline{T_I}$ (sec)	1.28 (0.37)	1.08 (0.34)	0.90 (0.22)
$\overline{T}_{tot}$ (sec)	2.89 (0.71)	2.40 (0.65)	1.97 (0.46)
DC (%)	44 (3)	45 (3)	45 (3)

Ratios

Results are presented in Table II.

Table II. Summary of Ratios

	Light Work Mean (SD)	Moderate Work Mean (SD)	Heavy Work Mean (SD)
$PIF_{max}: \dot{V}_E$	4.2 (0.8)	4.0 (0.5)	3.6 (0.5)
$\overline{PIF}: \dot{V}_E$	3.3 (0.4)	3.2 (0.3)	3.1 (0.3)
$V_{peak\ 5\%}: \overline{V_t}$ (%)	12.9 (0.60	13.1 (0.5)	12.9 (0.4)
$V_{peak\ 10\%}: \overline{V_t}$ (%)	24.4 (0.8)	24.6 (0.8)	24.8 (1.0)
$V_{peak\ 25\%}: \overline{V_t}$ (%)	53.9 (3.0)	54.0 (2.8)	55.1 (3.1)

$PIF_{max}: \dot{V}_E$

The ANOVA revealed a significant effect of workload with an F-value of 5.713 ($p < 0.01$). The general trend showed a decrease in the $PIF_{max}: \dot{V}_E$ ratio from 4.2 to 4.0 to 3.6 for light, moderate, and heavy exercises, respectively. A post hoc pairwise comparison revealed that the heavy exercise condition was significantly different from both light and moderate exercise, but moderate and light were not significantly different from each other.

$\overline{PIF}: \dot{V}_E$

A statistically significant effect of workload was found with an F-value of 7.560 ($p<0.01$). The general trend showed a slight decrease in the $\overline{PIF}: \dot{V}_E$ ratio from 3.3 to 3.2 to 3.1 for light, moderate, and heavy exercises, respectively. A post hoc pairwise comparison revealed that the heavy exercise condition was significantly different from both light and moderate exercise, but moderate and light were not significantly different from each other.

$V_{peak+/-5\%}: \overline{V_t}$

The ANOVA revealed no significant effect of workload. In other words, as workload increased, the volume of the defined peak region relative to the mean tidal volume did not change. The overall average percentage (ratio) across all three workloads was 12.9%. This indicates that the average volume within the defined peak inhalation region was slightly over one eighth of the average inhalation volume.

$V_{peak+/-10\%}$: $\overline{V_t}$

The ANOVA revealed no significant effect of workload. In other words, as workload increased, the volume of the defined peak region relative to the mean tidal volume did not change. The overall average percentage (ratio) across all three workloads was 24.5%. This indicates that the average volume within the defined peak inhalation region was roughly one quarter of the average inhalation volume.

$V_{peak+/-25\%}$: $\overline{V_t}$

The ANOVA revealed no significant effect of workload. In other words, as workload increased, the volume of the defined peak region relative to the mean tidal volume did not change. The overall average percentage (ratio) across all three workloads was 53.9%. This indicates that the average volume within the defined peak inhalation region was over one half of the average inhalation volume.

DISCUSSION

The intent of this research was to develop a modernized version of the baseline data from the work provided by Silverman's group over 60 years ago (Silverman et al., 1943). The goal was two fold: 1) to acquire, process, and analyze ventilation and peak inspiratory airflows for specified work intensities and 2) to provide an updated representative set of ventilation data of the general working population for three workloads (light, moderate and heavy).

The metabolic measures of heart rate and oxygen consumption confirm that on average the population was working at the desired relative work levels of 40, 60, and 80% of their maximal aerobic capacity. The ratings of perceived exertion scores of light, moderate, and heavy also agree with the metabolic values. Furthermore, by allowing participants four minutes of exercise at each work level prior to data collection, all breaths analyzed during the two-minute sample period were stable. Research has shown that at the onset of exercise, a minimum of 3 minutes is required to achieve a steady-state for ventilation measures such as $\dot{V}O_2$ (Barstow, 1994).

Airflow measurements were acquired using a pulmonary gas-exchanged system with a widely accepted level of accuracy, sensitivity, and reproducibility (Porszasz et al., 1994; Walschlager et al., 1996). Of particular interest to this research is the ability to more precisely focus upon and thoroughly examine the peak regions of breath inhalations. The high sampling rate allowed for increased precision in the analysis and interpretation of peak inspiratory airflows.

These results indicate a significant reduction of the ratios $\overline{PIF}:\dot{V}_E$ and PIF_{max}: $\dot{V}_E$ during heavy exercise compared to light and moderate exercise. It is expected that minute ventilation and peak inhalation flow will both increase as workload increases, however; the rate at which PIF and $\dot{V}_E$ increased appeared to be disproportional. Further analysis of the data showed that from moderate to heavy exercise $\dot{V}_E$ increased considerably (52.5%) compared to the increase of PIF_{max} (37.5%) and $\overline{PIF}$ (45.5%). The most plausible explanation for this effect is that the duration of airflow surrounding the PIF is driving $\dot{V}_E$, in other words PIF is achieved and the high flow rate is sustained for a greater period of time during periods of heavy exertion. What this does not account for is the observed difference between PIF_{max} and $\overline{PIF}$.

PIF has historically been analyzed by looking within a small sample for the maximum PIF (Silverman et al., 1943) or a series of peaks within a limited number of consecutive breaths (Kaufman and

Hastings, 2005). Both analysis techniques are limited in that they have a small set of representative data, i.e. Kaufman analyzed a series of only ten consecutive breaths during the period of heavy work. These methods do not account for the variability inherent to human breathing. For this study, the average sample size per exercise level per participant was slightly over 50 breaths, allowing for a more accurate generalization of peak inspiratory flow and ventilation when using the $\overline{\mathrm{PIF}}$ method which may more accurately represent the true breathing pattern of the individual.

This study has sought to explore a sample more typical of the average working population rather than a narrowly defined group of individuals. While this adds more variability to the data, it may provide a depiction of breathing patterns that are more indicative of the typical working adult. Further analysis of the ventilation results and how they compare to previous research can be found in the companion paper (Janssen et al., 2005).

CONCLUSIONS

While this research helps to modernize and establish baseline ventilation data, it does not diminish prior work by Silverman et al. (1943) and Kaufman and Hastings (2005). In fact, these findings expand upon and validate their results. Furthermore, this research does not directly address breathing in the presence of resistance, nor does this design attempt to include working populations with above average cardiovascular fitness. The direction of future research should attempt to study the effects of workloads (as defined in this study) in the presence of breathing resistance (i.e. respirators) on ventilation and peak inspiratory airflow using a similar research paradigm.

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