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# WORKPLACE BREATHING RATES: DEFINING ANTICIPATED VALUES AND RANGES FOR RESPIRATOR CERTIFICATION TESTING

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Test methods currently used by the National Institute for Occupational Safety and Health (NIOSH) are designed to assure that respirators meet a minimum level of efficacy when tested under standard laboratory protocols. For air-purifying respirators (APRs), the primary performance tests most affected by airflow rate are filter gas-life capacity, particulate filter efficiency, and respirator breathing resistances. Presently, NIOSH measures all three parameters using constant-rate airflow conditions. An analysis of the measured and estimated minute volumes contained in the literature indicated a range from about 8 to 162 $L\cdot min^{-1}$ for unencumbered ventilation and work activities that spanned from mild to exhaustive. The mean minute volume of the distribution was 38.5 ± 16.6 $L\cdot min^{-1}$, and the median was 33.6 $L\cdot min^{-1}$. Based on an empirical relationship between minute volume and peak inspiratory flow (PIF), peak flows between 72 $L\cdot min^{-1}$ and 183 $L\cdot min^{-1}$ would be expected for the mean minute volume for 38.5 $L\cdot min^{-1}$. The anticipated range of PIF rates for the 95th percentile minute volume is between 182 $L\cdot min^{-1}$ and 295 $L\cdot min^{-1}$. The results of this literature review suggest an increase in cyclic flow rates used for respirator certification testing should be considered to better represent ventilation rates found in the workplace.

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# EXECUTIVE SUMMARY

Test methods currently used by the National Institute for Occupational Safety and Health (NIOSH) are designed to assure that all respirators of a given type will meet a minimum level of efficacy when tested under standard laboratory protocols. The relevance and adequacy of airflow rates used in respirator certification testing has been a longstanding debate. The concern is that the current test flow rates substantially underestimate real world values, implying that filters certified under existing standards may not provide adequate protection. For qualifying air-purifying respirators (APRs), the primary performance tests most affected by airflow rate are filter gas-life capacity, particulate filter efficiency, and respirator breathing resistances. Presently, NIOSH measures all three parameters using steady, constant-rate airflow conditions. This report reviews concepts of human respiration pertinent to respirator certification, describes ventilation rates reported for occupational work activities, and reviews the impacts of respirator wear on ventilation.

The standard measure of respiration used to quantify respirator performance is minute volume, which represents the volume of air exhaled in one minute. Other ventilatory parameters of interest are peak inspiratory flow rate (PIF) and mean inspiratory flow rate. The instruments required to accurately quantify these ventilatory parameters are cumbersome and, thus, are impractical to use during most occupational activities. As a result, few data are available that quantify workplace activities. The data from many work rate studies present values for metabolic workload measured as oxygen consumption rate or heart rate. Empirical relationships developed by Hagan and Smith (51) and Baba *et al.* (10) were used to estimate minute volumes from the oxygen consumption rates. This allowed the inclusion of a greater number of studies and permitted analysis over a wider range of occupational activities.

An analysis of the measured and estimated minute volumes indicated a range from about 8 to 162 $L \cdot min^{-1}$ for unencumbered ventilation and work activities that spanned from mild to exhaustive. The mean minute volume of the distribution was 38.5 ± 16.6 $L \cdot min^{-1}$ and the median was 33.6 $L \cdot min^{-1}$. The mean is similar to the 40 $L \cdot min^{-1}$ cyclic flow rate currently employed in system-level chemical agent testing required by the NIOSH for certification of Self-Contained Breathing Apparatus (SCBA) and APRs to chemical, biological, radiological, and nuclear (CBRN) standards. However, a higher cyclic flow rate may be necessary to account for a greater percentage of ventilation rates that occur in the workplace as the 95th percentile for minute volume was 73.3 $L \cdot min^{-1}$. If the desire is to encompass a higher percentage of possible ventilation rates independent of the workplace, the recommendation would be to use the maximum minute volume of 114 ± 23 $L \cdot min^{-1}$ measured by Blackie *et al.* (15) for 20 to 29 year old males during maximal exercise.

The literature review indicated that PIF rates generally increase exponentially with increasing work rate. Based on an empirical relationship between minute volume and PIF, peak flows between 72 $L \cdot min^{-1}$ and 183 $L \cdot min^{-1}$ would be expected for the mean minute volume of 38.5 $L \cdot min^{-1}$. The anticipated range of PIF rates for the 95th percentile minute volume is between 182 $L \cdot min^{-1}$ and 295 $L \cdot min^{-1}$. Thus, a PIF of approximately 300 $L \cdot min^{-1}$ would adequately represent 95% of the peaks occurring during occupational task performance. However, PIF rates in excess of 300 $L \cdot min^{-1}$ have been measured during high intensity work. Estimates of PIF rates based on the minute volumes measured by Blackie *et al.* (15) indicate that the upper limit of PIF rate is between 430 and 500 L·min$^{-1}$. However, application of a constant airflow rate of equal to the PIF upper limit would not be representative of real use conditions for most, if not all, respirator types. Therefore, it is recommended to test PIF impacts under cyclic flow conditions representative of human ventilation to gain an understanding of respirator or filter performance under extreme flow conditions.

According to the literature, respirator wear has little impact on the minute volumes measured during resting and low intensity work conditions. However, maximum values for minute volume and PIF will generally be lower than those achieved for unmasked test activities, particularly during heavy work with APR and SCBA respirators. Supplied air systems appear to have less of an impact on ventilation by comparison. Despite the apparent dampening impacts of APR and SCBA systems on maximum ventilation values, the current recommendation is to utilize data for the unencumbered state for test flow rates and not to establish multiple flow rate criteria based on respirator types.

This review reemphasized the gap in data pertaining to human breathing responses to real-world daily activities. Despite the potential shortcomings of the empirical relationships used for estimating minute volumes and PIF rates, this review serves as a first step towards defining ventilation responses in the workplace. These findings suggest that an increase in cyclic flow rates used for CBRN certification testing should be considered to better represent ventilation rates found in the workplace.

# PREFACE

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# WORKPLACE BREATHING RATES: DEFINING ANTICIPATED VALUES AND RANGES FOR RESPIRATOR CERTIFICATION TESTING

## 1. INTRODUCTION

Test methods currently used by approval agencies are designed to assure that all respirators of a given type will meet a minimum level of efficacy when tested under standard laboratory protocols. The primary performance parameters most affected by airflow rate that are used to qualify air-purifying respirators (APRs) are filter gas-life capacity, particulate filter efficiency, and respirator breathing resistances. Presently, the National Institute for Occupational Safety and Health (NIOSH) measures all three parameters using steady, constant-rate airflow conditions. NIOSH-approved non-powered APR chemical cartridges and canisters (filter systems) are tested at a constant flow rate of 64 liters per minute ($L \cdot min^{-1}$). Powered air-purifying respirator chemical filters are tested at 115 or 170 $L \cdot min^{-1}$ constant flow. All NIOSH-approved particulate filters are tested using an 85 $L \cdot min^{-1}$ flow rate. For all filter testing, the airflow is divided equally between the number of filters used in the filter system (usually one to three depending on the type and design of the respirator). The breathing resistance for all non-powered APRs is measured in the breathing zone of the respirator, mounted on a test fixture, using a constant flow rate of 85 $L \cdot min^{-1}$. This flow rate is based on the assumption that 85 $L \cdot min^{-1}$ represents the maximum average flow rate into or out of the lungs during 30 minutes of sustained work.

The relevance and adequacy of airflow rates used in respirator certification testing has been a longstanding debate. The concern is that the current test flow rates substantially underestimate real world values, implying that filters certified under existing standards may not provide adequate protection. In general, the gas life provided by a respirator filter will decrease with increased airflow velocity since the time the contaminant stays in contact with the sorbent material (residence time) is significantly reduced.(18, 109, 122) Thus, high peak flow rates during inhalation can result in shorter filter breakthrough times.(88) Filter gas-life performance against chemi-adsorbed contaminants, as opposed to those removed by physical adsorption, is particularly impacted since the residence time can be too short to allow sufficient reaction with the impregnates. The contaminant will thus penetrate the sorbent bed much quicker than if the filter was challenged under more moderate airflow conditions.

The collection efficiency of both mechanical and electret particulate filters will also decrease with increasing airflow velocity due to a shift towards the lower end of the size range of the most penetrating particle size (MPPS).(83, 85) For respirator filters the MPPS ranges from approximately 0.1 to 0.3 μm count median diameter.(64, 123) In general, electret filters are more prone to penetration of particles under high flow conditions. This is true because high flow rates reduce the residence time that is needed for particles to be effectively captured by the two most prevalent electrostatic capture mechanisms (electrophoretic and dielectrophoretic capture).(37, 123)

In addition to concerns about filter performance, some have questioned the ability of supplied air pressure-demand systems to maintain positive pressure within a respirator so that no inward leakage of a toxin would occur in the absence of an ideal seal of the respirator to the face under heavy work conditions that produce inhalation airflows that exceed current certification flow rates.(30, 119) Others have recently debated this same concern in reference to powered air-purifying respirators.(14)

This report attempts to review the concepts of human respiration pertinent to respirator certification, to describe ventilation rates reported for occupational work activities, and to review the impacts of respirator wear on ventilation. Since ventilation rates are not available and are not likely ever to be available for all physical activities, this review includes a wide range of physical activity studies that were utilized to provide estimates of ventilation rates for multiple occupational tasks. The adequacy of current respirator certification flow rates will be discussed based on the findings of this review.

## 2. BACKGROUND

A standard measure of respiration used to quantify respirator performance is minute volume ($\dot{V}E$), which is simply the volume of air that is *exhaled* in one minute. Minute volume (or minute ventilation) is equal to the product of the volume of air respired in each breath, or the tidal volume ($V_T$), and the number of breaths in a minute ($f$). Minute volumes during the inhalation cycle of breathing ($\dot{V}I$) can also be determined if tidal volumes are measured during inhalation. However, the volumes of inhaled and exhaled air are usually slightly different ($\dot{V}I \leq \dot{V}E$) because the conducting airways of the respiratory system condition inhaled air by warming it to body temperature and saturating it with water vapor before it is exhaled. Nevertheless, for the purpose of this review, data for $\dot{V}I$ and $\dot{V}E$ will be considered equal unless otherwise stated.

At rest, minute volumes of respiration typically range between 5 and 8 $L{\cdot}min^{-1}$.(48) From rest, minute ventilation increases semilinearly with increasing rates of exercise up to maximal levels. Ventilation rates as high as 200 $L{\cdot}min^{-1}$ have been reported in extreme cases.(127, 151)

Other ventilatory parameters of interest used to relate respirator performance to human respiration include peak inspiratory flow rate (PIF) and mean inspiratory flow rate, or the ratio of tidal volume to inspiratory time ($V_T/T_I$). Peak inspiratory flow rate describes the maximum rate of airflow attained during inhalation. As previously mentioned, high peak flow rates can result in shorter contaminant breakthrough times of filtering elements. In addition, PIF rates have a direct impact on the ability of supplied-air, demand systems to maintain positive pressure within the breathing zone of a respirator. In order to maintain positive pressure during inhalation, any pressure-demand respirator's airflow capability must exceed PIF. Mean inspiratory flow rate ($V_T/T_I$) is an index of inspiratory motor input or drive that generally increases linearly with $\dot{V}E$.(24, 105) In reference to respirator usage, $V_T/T_I$ serves as an indicator of the mean rate of airflow during inhalation and provides information concerning the duration of flow.

## 2.1 Measuring Ventilation.

Several methods of measuring ventilatory volumes and flow rates can be used, either directly as part of a breathing circuit or indirectly to measure volumes from a collection container. While ventilatory flow is usually measured, many other parameters of the respiratory system can be derived from measured quantities of volume or flow. In general, ventilation and flow have been measured using gas meters, spirometers, pneumotachographs, turbine flow meters, rotameters, hot-wire anemometers, ultrasonic flowmeters and, to a lesser extent, plethysmographic techniques. For a detailed discussion of some of these methods, as well as the advantages and disadvantages of each, refer to Wasserman *et al.*(146) A brief discussion of each method follows.

A gas meter acts as a volumetric turnstile, sequentially filling compartments of known volume and recording the number of times each has been filled. It is classified as dry or wet, depending on the seal that is used in the mechanism. A dry gas meter is used to measure volumes of respired air collected in Douglas bags or meteorological balloons, or used directly in either the inspired or expired side of a breathing valve circuit. A dry gas meter is better suited for a manually operated data collection set up with an intermittent collection of respired air.

Perhaps the oldest device to measure ventilatory volumes is the spirometer, which can be used to measure collected volumes, calibrate other volume and flow devices, or measure volumes directly in a manually operated system. A spirometer by itself only measures volumes. To measure flow (volume per unit time), a means of recording changes in volume with time must be devised. Spirometers can also be connected to a computer to obtain volumes and flow rates.

Turbine flow transducers use a lightweight impeller to directly measure airflow volumes. Rotation of the impeller can be related to airflow and respired air volumes using optical, electrical, or mechanical detection systems. Such devices have gained wide acceptance, particularly for breath-by-breath ventilatory measurements. However, the speed of the impeller is sensitive to water or saliva deposition.

Rotameters are widely used in gas delivery systems for continuous flow measurements. Most designs utilize a vertical tapered tube containing a bobbin or ball that is supported by the airflow as it passes upwards through the tube. Rotameter calibration is gas-specific so, for accuracy, its use must be restricted to the same gas or it must be re-calibrated if a new gas is used. Inaccuracy results from anything that causes the bobbin to stick in the tube. Backpressure caused by downstream airflow resistance also leads to inaccurately low readings.

In a hot-wire anemometer, an electrically heated wire is placed in the airflow pathway and is cooled by the flow. The degree of cooling depends upon the flow rate, which can thus be derived. This cooling effect occurs with flow in either direction, so the hot-wire anemometer can be modified to determine both inspiratory and expiratory flows when placed on only one side of the breathing circuit. Hot-wire anemometry is generally extremely accurate.

Ultrasonic flowmeters work on the principle that when an ultrasound signal is being transmitted within a flowing gas, its velocity changes in proportion to that of the gas flow. When the gas flow and ultrasound signal are in the same direction, an increase in signal velocity occurs.

Conversely, when the signal is against the direction of gas flow, its velocity decreases. The usual design incorporates a pair of ultrasound beams aimed in opposite directions, each with a sensor. When no flow is present, the velocity of the two beams is equal, and pulses of ultrasound arrive at the sensors simultaneously. When flow occurs, there is a time difference between signal detection at the sensors from which gas velocity and flow rate can be calculated.

The pneumotachograph is the most common device used for flow measurements in respiratory mechanics. In a pneumotachograph (both Fleisch and screen pneumotachographs), a resistance is put in the gas flow pathway and the resulting pressure drop is measured rapidly and accurately using a differential pressure transducer, from which flow rate and volume are calculated. Pneumotachographs generate differential pressures proportional to the volume flow and viscosity of gas, but independent of gas pressure.(141) Flow-to-differential pressure calibration of a pneumotachograph depends on gas viscosity, temperature, and humidity, as well as the up- and downstream geometry of the tube.(141-143) A heating element is sometimes incorporated to prevent the build-up of condensation that could compromise accuracy. Thus, pneumotachographs require routine calibration under conditions as close as possible to those under which measurements are performed. Even so, the pneumotachograph has the advantages of compactness, low flow resistance, and suitability for accurate measurements of airflow. Measurements can be made at various points in the breathing circuit, and a pair of sensors is often used so that inspired and expired volumes can be measured independently. The Fleisch pneumotachograph is available in six different sizes, with larger sizes intended for measuring higher flow rates. Flow rates developed by exercising adults generally indicate that a No. 3 Fleisch pneumotachograph is appropriate, providing a balance between linearity in flow rates up to 10 $L \cdot s^{-1}$ and adequate sensitivity at low flows.(146)

Despite the utility of dry gas meters, spirometers, pneumotachographs, and turbine flow meters, all are somewhat invasive in that they require a direct connection to the breathing circuit and can cause minor alterations in an individual's natural pattern of breathing.(48, 71, 110) Respiratory inductive plethysmography is the most widely accepted method for quantitative non-invasive respiratory measurements. Respiratory inductive plethysmography (RIP) employs sensors to measure changes in a cross-sectional area of the rib cage and abdominal compartments during a respiratory cycle. The sensors consist of arrays of sinusoidally arranged copper wires woven into elastic bands that are excited by a low-current, high-frequency (300 kHz) electrical oscillator circuit. Movement of the rib cage or abdominal compartments causes the sensors to generate magnetic fields, which are measured as voltage changes over time (i.e., waveforms). In order to correlate a cross sectional area of the rib cage and abdominal compartments with respired volume, the device must be calibrated for each individual user using a spirometer. When properly calibrated, the RIP will provide reasonable estimates of volume and timing components of the breathing cycle. However, due to difficulties in maintaining positioning of the ribcage and abdominal sensor bands once calibration has been completed, acceptance of RIP for measuring ventilation is limited to non-exercise studies of ventilation such as speech ventilation and clinical monitoring. Researchers that have attempted to use RIP for measuring ventilation during physical activities that exceed resting workloads have reported varying degrees of precision when compared to other standards.(20, 22, 126)

## 2.2 Measuring Energy Expenditure Rates.

Two general methods exist for measuring an individual's rate of energy expenditure: direct and indirect calorimetry. Direct calorimetry is based on the principle that the amount of heat output from the body provides a direct measure of metabolic rate. However, since techniques for collecting such data are unsuitable for field conditions, indirect measures of metabolism are commonly employed. Indirect calorimetry is based on knowledge of the oxidation rate of food energy, which is, in turn, dependent upon oxygen utilization by the metabolizing tissue.

For the purpose of most energy-expenditure studies, indirect calorimetry consists of measuring the volume of expired air per unit of time and determining the percentage of oxygen expired.(148) By calculating the difference between the percentage of oxygen in inspired and expired air, the percentage utilized is determined. This value is then multiplied by the volume of expired air and corrected to standard temperature and atmospheric pressure conditions (STPD) to determine the amount of oxygen consumed. Commonly referenced equipment and techniques available to measure the volume of expired air from a subject and to collect a sample of expired air for gas analysis include the Douglas bag method, commercially available and customized exercise test systems or metabolic carts for computer-controlled indirect calorimetry, and various ambulatory gas analysis systems such as the Max Planck or Kofranyi-Michaelis (K-M) respirometer, the Oxylog, the Cosmed K2 and K4, and the TEEM 100. All require use of a flow-measuring device within the breathing circuit for sample collections. Summary descriptions of this equipment can be found in Durnin and Passmore,(35) Bassey and Fentem,(11) Wasserman *et al.*,(146) and Patton.(111) A brief overview of select indirect calorimetry techniques is provided below.

The Douglas bag method is both simple and reliable for collecting expired air samples over periods of 5 to 15 minutes.(27) The limitations of this method result from interference with locomotive activity caused by the need to carry a cumbersome 100-200 L bag, and the limited duration of the collection or sampling period because of bag capacity. Once an expired air sample is collected, its percentage of oxygen is analyzed and the volume is then recorded using a dry gas meter.

The K-M respirometer, carried in knapsack fashion, is much smaller and lighter (3 kg) than the Douglas bag so that interference with normal activities is far less severe. The system uses a dry gas meter for measuring total expired air volume and temperature. An aliquoting device continuously extracts a small amount of each breath into a sampling bladder for subsequent analysis of oxygen and carbon dioxide content in a laboratory. Thus, it can measure consumption over extended periods at low metabolic rates, although the sampling bladder generally fills after only 10 minutes during moderate work. The major limitation of the K-M respirometer is that its design causes the equipment to begin to resist airflow at high ventilation rates. Consequently, oxygen consumption levels tend to be under-recorded when $\dot{V}_E$ exceeds approximately 60 L·min$^{-1}$. Nevertheless, this method has proved highly reliable for normal work activities. A complete description of this apparatus and the sources of inaccuracy are provided in Consolazio *et al.* (27) and Consolazio.(26)

The Oxylog is a lightweight, battery-driven instrument for measuring oxygen consumption and ventilation. The instrument is equipped with a half-mask that has a turbine flow meter attached to the inspiratory port for measuring $\dot{V}_I$. The accuracy of the Oxylog has been validated in both laboratory and field tests that indicate the system is sufficiently accurate for field measurements of $\dot{V}_E$.(56, 91) Likewise, the system appears to be well suited for studies in which duration and intensity of activities need to be well defined.(11)

The Cosmed K2 and newer K4 systems also measure breath-by-breath gas exchange and ventilation using a facemask connected to a portable unit. The system has been validated for both maximal and submaximal work intensities (57, 100) and shows a strong correlation to values obtained with a metabolic cart.(114)

Finally, the TEEM 100 (Total Energy Expenditure Measurement system) uses an open-circuit continuous sampling system for the measurement of oxygen uptake and a pneumotachograph is positioned in a facemask for measuring $\dot{V}_E$. The validity of the TEEM 100 has been demonstrated for submaximal exercise testing, but data recorded during maximum exercise testing indicates that $\dot{V}_E$ data obtained with the TEEM 100 is significantly lower compared to a metabolic cart system.(111)

An alternative to indirect calorimetry is monitoring activity heart rates. This technique is based on an association between heart rate and oxygen consumption or energy expenditure. This relationship, however, does not hold for either sedentary activities or very high levels of exertion. Moreover, although the relationship of heart rate to energy expenditure may be highly significant in a single subject at any one time, it can vary considerably between individuals and within one individual under different conditions. In order to deal with these problems and increase the precision of the method, it is first necessary to establish heart rates and associated oxygen consumption rates for each subject for various levels of physical exertion. One must then develop a regression equation for each subject in order to estimate energy expenditure for monitored activities.

## 2.3 Classification of Work Based on Oxygen Consumption.

Measurements of oxygen consumption have been used to determine energy expenditures of a great number of human activities. As such, several classifications of workload have been proposed based on these data.(8, 42, 74) However, inconsistencies in terminology used for work classes and rates of oxygen uptake assigned for the various work categories make it difficult to quantify exactly what is meant by light, moderate, or heavy work. For example, Johnson *et al.* (74) categorize an oxygen consumption rate ($\dot{V}O_2$) of 2.2 L·min$^{-1}$ as 'moderate' work. In comparison, Åstrand and Rodahl (8) consider $\dot{V}O_2$ levels between 0.5 L·min$^{-1}$ and 1.0 L·min$^{-1}$ to be 'moderate' work while data presented by Fox *et al.* (42) suggest that $\dot{V}O_2$ levels between 0.75 L·min$^{-1}$ and 1.5 L·min$^{-1}$ define 'moderate' work. In view of the great differences in physical work capacity or fitness of the working population, and working postures, whether work is intermittent or continuous, and work environmental conditions, attempts to rigidly compartmentalize the physical work of occupational activities in terms of oxygen consumption may never be realized. Nevertheless, the data provided in Table 1 are included as a general guide for classification of physical work. The work classifications presented in Table 1 were selected because they included estimates of both minute ventilation and breathing rates and because of their relative agreement with $\dot{V}O_2$ levels and work categories published by Åstrand and Rodahl.(8) Another way to understand the relative intensities associated with various levels of work, whether they are based on $\dot{V}O_2$, heart rates, or even $\dot{V}E$, is to be cognizant of how they compare to common values at rest. In general, $\dot{V}O_2$ at rest is between 0.25 and 0.3 $L \cdot min^{-1}$. Also, about six to eight liters of air are being ventilated per minute. With this knowledge, it is easy to understand that an activity that requires an oxygen consumption of 3.0 $L \cdot min^{-1}$ is ten times more intense than rest. Likewise, an individual breathing at a rate of 80 $L \cdot min^{-1}$ is moving about ten times more air through the lungs than that needed for a resting metabolism. Knowing such relationships will assist in understanding the intensity of work.

## 2.4 Estimation of Ventilation Using Oxygen Consumption.

Accurate measurement of breathing rates and patterns normally requires that the subject breathe through a mouthpiece and one-way valve, and that the individual be instrumented with a flow-measuring device, data gathering hardware, and recording equipment. This is impractical during most everyday activities. As a result, few data are available that quantify workplace breathing parameters. However, some of the occupational task performance literature that was reviewed for this effort did include measurements of minute volumes, but the majority of the papers did not report these data. The data from many work rate studies present values for metabolic workload measured as $\dot{V}O_2$, which, again, is the amount of oxygen utilized by the body's metabolic processes in a given time. However, the majority of energy expenditure literature measured activity heart rates and used predetermined relationships between heart rate and $\dot{V}O_2$ of individual test participants to estimate $\dot{V}O_2$. Since $\dot{V}O_2$ data for various physical activities have been widely reported, it was believed that such data could be used to estimate $\dot{V}E$ based on an understanding of the relationship between the volume of air respired per liter of oxygen consumed, or the ventilatory equivalent for oxygen.

The ventilatory equivalent for oxygen is defined as the ratio of minute volume to oxygen consumption ($\dot{V}E/\dot{V}O_2$). The value of this ratio varies from person to person based upon an individual's oxygen uptake efficiency, lung physiology, and metabolic state. In general, the ventilatory equivalent for oxygen ranges from approximately 20 to 25 (unitless measure) from rest to moderate levels of physical activity ($\dot{V}O_2 \leq 2\ L \cdot min^{-1}$).(8) Some researchers have reported that $\dot{V}E/\dot{V}O_2$ equals about 30 for oxygen uptake levels above 2.5 $L \cdot min^{-1}$.(101, 147) Layton (84) compiled a dataset of 159 measurements of $\dot{V}E$ and $\dot{V}O_2$ reported in the open literature to evaluate the ratio of $\dot{V}E$ to $\dot{V}O_2$. This analysis showed a linear relationship between the two variables and indicated that most of the values of $\dot{V}E/\dot{V}O_2$ fall within the 68% confidence interval of a lognormal distribution. The $\dot{V}E/\dot{V}O_2$ values corresponding to this distribution were between 23 and 32.

## Table 1. Classification of Physical Work Based on Metabolic and Ventilatory Parameters

| | | **Metabolic Rate** | | | **Ventilation** | | |
|---|---|---|---|---|---|---|---|
| **Classification of work** | **Heart rate (min$^{-1}$)** | $\dot{V}O_2$ **(L·min$^{-1}$)** | $\dot{V}O_2$ **(mL·kg$^{-1}$·min$^{-1}$)** | **METS** | $\dot{V}E$ **(L·min$^{-1}$)** | **Rate (min$^{-1}$)** | **Length of time work can be sustained** |
| 1. Light | | | | | | | |
| a. Mild | < 100 | < 0.75 | < 10.5 | < 3 | < 20 | < 14 | Indefinite |
| b. Moderate | < 120 | < 1.5 | < 21.0 | < 6 | < 35 | < 15 | 8 hours daily on the job |
| 2. Heavy | | | | | | | |
| a. Optimal | < 140 | < 2.0 | < 28.0 | < 8 | < 50 | < 16 | 8 hours daily for a few weeks (seasonal work, military maneuvers, etc.) |
| b. Strenuous | < 160 | < 2.5 | < 35.0 | < 10 | < 60 | < 20 | 4 hours two or three times a week for a few weeks (special physical training) |
| 3. Severe | | | | | | | |
| a. Maximal | < 180 | < 3.0 | < 42.0 | < 12 | < 80 | < 25 | 1 to 2 hours occasionally (usually in competitive sports) |
| b. Exhausting | > 180 | > 3.0 | > 42.0 | > 12 | > 80 | > 25 | Few minutes |

Adapted from Fox *et al.* (42)

In contrast to the findings of Layton,(84) some reports suggest that $\dot{V}_E$ increases in a curvilinear fashion while $\dot{V}_{O_2}$ increases linearly, particularly at high work rates.(10, 39, 51) Hagan and Smith (51) examined this apparent curvilinear relationship between exercise $\dot{V}_E$ and $\dot{V}_{O_2}$ during exhaustive incremental treadmill exercise in 45 male volunteers (mean age 32 years) who were actively engaged in daily running programs. These investigators reported that during incremental load work $\dot{V}_E$ increased exponentially with an increase in $\dot{V}_{O_2}$ even at low workloads. The correlation coefficient of the regression model was high ($r = 0.94$, $p < 0.0001$). The exponential regression equation that related $\dot{V}_E$ to $\dot{V}_{O_2}$ for the range of oxygen consumption rates that were recorded (0.9 L·min$^{-}$1 to 4 L·min$^{-1}$) was

$$\dot{V}_E\ (\text{L·min}^{-1}) = 16.27\ e^{(0.515 \cdot \dot{V}_{O_2})} \qquad (1)$$

with $\dot{V}_{O_2}$ in L·min$^{-1}$. This equation provides a possible means for estimating $\dot{V}_E$ from $\dot{V}_{O_2}$ data reported for occupational energy expenditure literature, at least for $\dot{V}_{O_2}$ values between 0.9 L·min$^{-1}$ and 4 L·min$^{-1}$. However, the findings of Hagan and Smith (51) may be limited to healthy, physically active, male subjects. Considering that the demographic make-up of the worker population includes individuals with a wide range of physical fitness levels as well as varying degrees of cardiovascular and pulmonary health, estimation of $\dot{V}_E$ based solely on this exponential function may not present a true representation of ventilation rates anticipated for the general working population.

Baba *et al.* (10) also reported an exponential relationship between $\dot{V}_E$ and $\dot{V}_{O_2}$, but for a more diverse subject population that included 12 patients with chronic heart failure as well as eight female participants (total $n = 38$). The exponential regression equation that related $\dot{V}_E$ to $\dot{V}_{O_2}$ for this study was

$$\dot{V}_E\ (\text{mL·kg}^{-1}\text{·min}^{-1}) = 207\ e^{(0.059 \cdot \dot{V}_{O_2})} \qquad (2)$$

when $\dot{V}_{O_2}$ is expressed in mL·kg$^{-1}$·min$^{-1}$, or

$$\dot{V}_E = 14.49\ e^{(0.842 \cdot \dot{V}_{O_2})} \qquad (3)$$

with both $\dot{V}_E$ and $\dot{V}_{O_2}$ in L·min$^{-1}$. The correlation coefficient of this regression model was also high ($r = 0.94$). The range of oxygen consumption rates that were observed in this study was not explicitly reported, however interpolation of data presented in one of the report figures indicates that the range of $\dot{V}_{O_2}$ was between approximately 5 and 28 mL·kg$^{-1}$·min$^{-1}$. This range would permit calculation of reasonable estimates of ventilation for workloads lower than those tested by Hagan and Smith (51) ($\dot{V}_{O_2}$ range of approximately 11.3 mL·kg$^{-1}$·min$^{-1}$ to 50 mL·kg$^{-1}$·min$^{-1}$ based on an average population weight of 80 kg).

It is important to note that both Baba *et al.* (10) and Hagan and Smith (51) found the relationship between $\dot{V}_E$ and $\dot{V}_{O_2}$ to be reliably expressed as an exponential function

$$\dot{V}E = ae^{(b \cdot \dot{V}O_2)} \tag{4}$$

where the $a$ parameter is the y-intercept of the regression equation and the $b$ parameter is the slope. The differences between equations (1) and (3) in the magnitudes of these parameters can be explained based on the different test subject populations. Baba *et al.* (10) found that parameter $a$ was significantly positively correlated with individual peak $\dot{V}O_2$ (i.e., $a$ was higher for individuals with higher peak $\dot{V}O_2$). Since high values of peak (or maximum) $\dot{V}O_2$ are an indication of a greater level of cardiorespiratory fitness, this would indicate that parameter $a$ would be greater for individuals with better fitness levels. Baba *et al.* (10) also found that parameter $b$ was significantly negatively correlated with individual peak $\dot{V}O_2$ (i.e., $b$ was smaller for individuals with higher peak $\dot{V}O_2$), indicating that a lower value of $b$ would be expected for those who have better cardiorespiratory fitness. Thus, the higher value for parameter $a$ and the lower value for parameter $b$ in equation (1) reflect the healthier, better fit subject population utilized by Hagan and Smith (51) for their study.

Independently, Fairshter *et al.* (39) also found an exponential relationship between $\dot{V}E$ and $\dot{V}O_2$. However, the data presented by these investigators did not provide an exponential function for their entire test subject population. As a means of further evaluating the exponential relationship between $\dot{V}E$ and $\dot{V}O_2$, we compiled data from multiple articles that reported oxygen consumption and ventilation. A total of 14 publications describing ventilation during exercise performance were reviewed, three of which reported individual subject data, while the remaining 11 reported group means.(9, 15, 41, 54, 55, 58, 73, 78, 80, 112, 115, 131, 140, 149) Of the 409 subjects that took part in these investigations, 68% were males and all were reported to be healthy. The total number of data points derived from the review was 118, representing 60 population means and 58 individual subject responses. A plot of minute ventilation versus oxygen consumption was developed based on the data presented in these articles (Figure 1). For instances where oxygen consumption values were reported relative to body weight (i.e., units of $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), the average weight reported for the test population was used to convert to absolute oxygen consumption ($\text{L}\cdot\text{min}^{-1}$).

The data in Figure 1 show a wide spread of minute volumes reported for similar levels of oxygen consumption, particularly at $\dot{V}O_2$ levels above 2 $\text{L}\cdot\text{min}^{-1}$. In addition, the scatter of $\dot{V}E$ data tends to lie between the exponential relationships of $\dot{V}E$ and $\dot{V}O_2$ found by both Baba *et al.* (10) and Hagan and Smith.(51) An exponential function was fitted to the reviewed data and the relationships between the Baba *et al.*, (10) Hagan and Smith,(51) and the dataset compiled in our literature review were assessed. The correlation coefficient of the regression model was significant ($r = 0.92$, $p < 0.001$), however the slope and *y*-intercept of the exponential function differed significantly from the exponential functions reported by Hagan and Smith (51) and Baba *et al.* (10) These findings indicate that the relationship between $\dot{V}E$ and $\dot{V}O_2$ can be adequately described as an exponential function. However, it appears that the relationship is dependent on subject characteristics. Considering that the subject population assessed by Baba *et al.* (10) may be more representative of the general worker population, and the fact that the exponential relationship reported by Hagan and Smith (51) was applicable to a wider range of oxygen uptake rates, it was reasoned that the prediction equations published by both investigators would provide reasonable estimates of minute volumes from oxygen consumption rates. However, in adopting this approach, estimates of $\dot{V}_E$ determined from the exponential relationships of both studies were only applied for the ranges of $\dot{V}_{O_2}$ for which each were established. In other words, the Hagan and Smith (51) equation was not used for $\dot{V}_{O_2}$ values below 0.9 $L \cdot min^{-1}$ and the Baba *et al.* (10) relationship was not applied for $\dot{V}_{O_2}$ above 2.2 $L \cdot min^{-1}$ (based on an assumed population weight of 80 kg; the average weight of the subjects was not published by Baba *et al.* (10)).

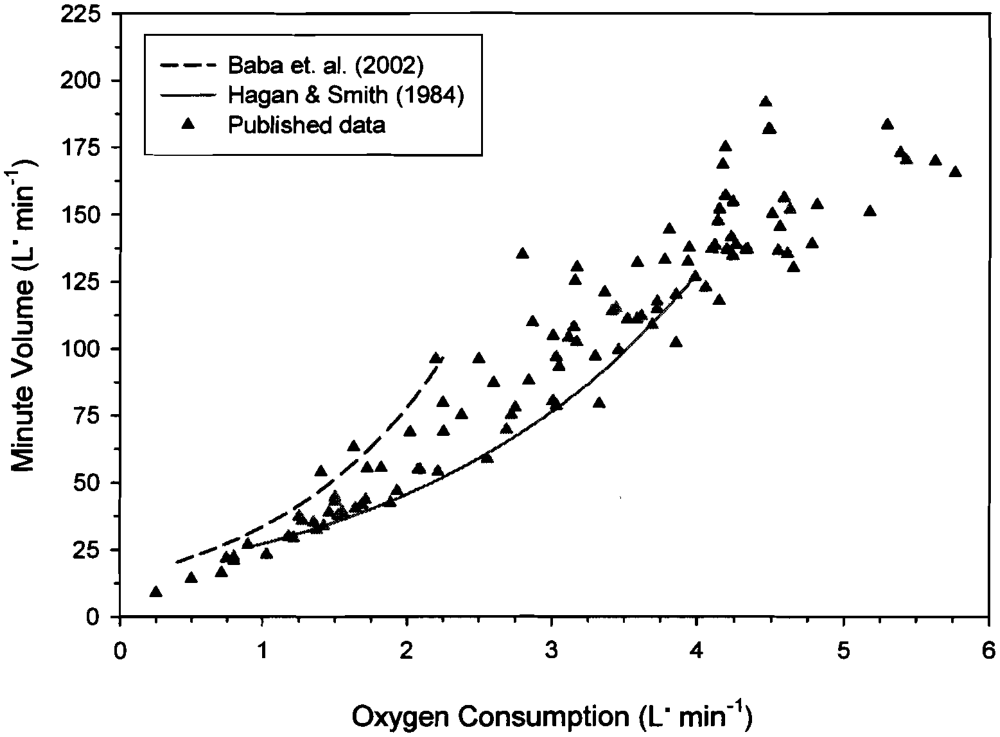

**Figure 1. Plot of $\dot{V}_E$ and $\dot{V}_{O_2}$ Data Obtained From Selected Literature (Scatter) Compared to the Exponential Functions Described by Hagan and Smith (51) and Baba *et al.* (10)**

## 3. UNENCUMBERED VENTILATION

### 3.1 Minute Ventilation During Maximal Exercise.

Maximal exercise testing permits a rapid yet thorough assessment of an individual's cardiorespiratory responses to exercise including the level of the subject's exercise limitation. Typically, such testing spans a tolerable work rate range from low to high levels during which large amounts of respiratory and cardiovascular data are collected up to and including the voluntary endpoint of testing. Many published reports have documented breathing patterns adopted by healthy humans during incremental exercise.(15, 44, 108, 139, 146) In general, it has been demonstrated in subjects with various fitness levels that increasing minute volumes are due to increases in both tidal volume and breathing frequency at low exercise intensities. At high exercise intensities increases in minute volume are accomplished mainly by increasing breathing frequency, with tidal volume showing a plateau.(44)

Normal values and ranges of ventilation at maximal exercise with respect to age, sex, and body anthropometrics have also been established using incremental testing. Blackie *et al.* (15) exposed 231 subjects (120 women; 111 men) to a symptom-limited maximal, progressive, incremental cycle ergometer exercise test. All subjects underwent a medical screening and physical examination, including spirometry for those who had a history of current or past smoking. Competitive athletes were excluded. The test subject population was dispersed in equal numbers (n =20) in ten-year age categories of 20-29 years, 30-39 years, 40-49 years, 50-59 years, 60-69 years, and 70-79 years for each sex, with the exception of men over 70 years of age (n = 11). Measurements of $\dot{V}E$, $V_T$, and $f$ were obtained at the end of each subject's exercise test when maximal performance had been attained. The mean values (± SD) for $\dot{V}E_{\max}$, $V_{T\max}$, and $f_{\max}$ are presented in Table 2 for each age group for both sexes. Average $\dot{V}E_{\max}$ was 97 ± 25 L·min$^{-1}$ for all male subjects and ranged from 66 ± 12 to 114 ± 23 L·min$^{-1}$ across age groups. For females, average $\dot{V}E_{\max}$ was 69 ± 22 L·min$^{-1}$ and ranged from 48 ± 12 to 87 ± 17 L·min$^{-1}$. Independent of age, $\dot{V}E_{\max}$ and $V_{T\max}$ were significantly greater ($p<0.001$) for males compared to females. There was no difference in $f_{\max}$ between men and women.

**Table 2. Mean Values for Ventilation at the End of Maximum Exercise**

| **Group and Age (yr)** | **$\dot{V}E_{\max}$ (L·min$^{-1}$)** | **$f_{\max}$ (breaths·min$^{-1}$)** | **$V_{T\max}$ (L)** |
|---|---|---|---|
| **Men** | | | |
| **20 – 29** | 114 ± 23 | 42 ± 8 | 2.7 ± 0.4 |
| **30 – 39** | 105 ± 30 | 40 ± 15 | 2.7 ± 0.6 |
| **40 – 49** | 102 ± 23 | 36 ± 7 | 2.9 ± 0.6 |
| **50 – 59** | 97 ± 15 | 36 ± 6 | 2.9 ± 0.3 |
| **60 – 69** | 83 ± 14 | 33 ± 6 | 2.6 ± 0.4 |
| **70 – 79** | 66 ± 12 | 30 ± 6 | 2.3 ± 0.4 |
| **Mean ± SD** | 97 ± 25 | 36 ± 9 | 2.7 ± 0.5 |
| **Women** | | | |
| **20 – 29** | 87 ± 17 | 41 ± 7 | 2.2 ± 0.5 |
| **30 – 39** | 88 ± 19 | 44 ± 8 | 2.0 ± 0.3 |
| **40 – 49** | 74 ± 15 | 35 ± 8 | 2.1 ± 0.4 |
| **50 – 59** | 60 ± 15 | 32 ± 8 | 1.9 ± 0.4 |
| **60 – 69** | 56 ± 14 | 33 ± 9 | 1.7 ± 0.2 |
| **70 – 79** | 48 ± 12 | 31 ± 7 | 1.6 ± 0.3 |
| **Mean ± SD** | 69 ± 22 | 36 ± 9 | 1.9 ± 0.4 |

Adapted from Blackie *et al.*(15)

Sue and Hansen (139) reported values similar to Blackie *et al.* (15) for $V_T$ (2.28 ± 0.43 L) and $f$ (41.6 ± 9.6 min$^{-1}$) at maximum exercise in a population of middle-aged men (mean age = 54 years, range 34 to 74 years). Comparable values of $\dot{V}_E$ have also been reported for specific age and gender groups and individual subjects at maximum efforts of incremental cycling exercise. Wasserman *et al.* (146) observed $\dot{V}_{E\,\max}$ values of 107 L·min$^{-1}$ for a 55 year old male executive, 89 L·min$^{-1}$ for a 59 year old retired male shipyard worker, 70 L·min$^{-1}$ for a 45 year old female homemaker, and 90 L·min$^{-1}$ for a 37 year old male shipyard machinist, values that all fall within age-specific data reported by Blackie *et al.* (15)

In a study of similar design to that of Blackie *et al.*, (15) Neder *et al.* (108) assessed breathing patterns during incremental exercise of 120 normal, healthy, sedentary individuals (60 males, 60 females) evenly distributed in age groups of 20-39 years, 40-59 years, and 60-80 years. Although these investigators were primarily interested in developing normative ventilatory data at selected submaximal ventilatory stresses, maximal $\dot{V}_E$ data were reported for each age group by sex. For females, Neder *et al.* (108) recorded average $\dot{V}_{E\,\max}$ values of approximately 76 ± 14, 67 ± 11, and 50 ± 10 L·min$^{-1}$ for the age groups of 20-39 years, 40-59 years, and 60-80 years. Maximal $\dot{V}_E$ averaged 120 ± 28, 99 ± 22, and 77 ± 12 L·min$^{-1}$ for the three ascending male age groups. Again, these values reflect the data reported by Blackie *et al.* (15) for a similar subject population. Therefore, the data presented in Table 2 serve as a reasonable representation of normal maximal ventilatory responses to exhaustive incremental exercise for a wide range of ages in both males and females.

Ventilation rates that exceed the values presented in Table 2 have been reported, with minute volumes in excess of 200 L·min$^{-1}$ found in some cases. Åstrand and Saltin (9) measured a maximal $\dot{V}_E$ value of 183.4 L·min$^{-1}$ in one test subject during constant rate exhaustive cycling. In fact, these researchers reported peak minute volumes that ranged from approximately 116 to 157 L·min$^{-1}$ dependent upon the type of maximal work that was performed. It should be noted, however, that these data were obtained on relatively well-trained males with relatively high aerobic capacities ($\dot{V}O_{2\,\max}$ > 4 L·min$^{-1}$). Maximal $\dot{V}_E$ of 180 to 190 L·min$^{-1}$ have also been reported in previous research using elite cyclists and oarsmen.(24, 55, 96, 97) This evidence indicates that very high rates of ventilation are possible, but suggest that only relatively well-conditioned athletes can achieve such high values.

### 3.2 Peak Inspiratory Flow Rates During Exercise.

Reports that document peak inspiratory flow (PIF) rate data are not common for normal, healthy individuals performing various levels of work. It is important to understand that PIF rates do not quantify sustained rates of inhaled airflow, but represent peak velocities of air movement during the inhalation phase of respiration. For example, a PIF rate of 200 L·min$^{-1}$ does not mean that an individual ventilated a total of 200 L of air in a minute but that the peak rate of air movement during inhalation was 200 L·min$^{-1}$. To put it another way, a PIF of 200 L·min$^{-1}$ is not equal to a minute volume ($\dot{V}_E$) of 200 L·min$^{-1}$.

Silverman *et al.* (131) investigated flow rates obtained from healthy males aged 16 to 44 while they were at rest and exercising at 0, 34, 68, 102, 136, 181, 226, and 271 watts (W) on a cycle ergometer. Each work rate was performed with just the air flow-measuring apparatus (inspiratory and expiratory resistances of 0.4 and 0.2 cmH$_2$O · L$^{-1}$· s) and with imposed inspiratory and expiratory resistances (to be addressed later). Peak inspiratory flow rates for the unencumbered condition were 40 ± 8, 49 ± 8, 63 ± 8, 84 ± 10, 100 ± 14, 149 ± 29, 194 ± 32, 254, and 286 L·min$^{-1}$ for the eight work rates from rest to maximum. The authors concluded that peak inspiratory flow rates increased exponentially with increasing work rate. The authors also compared the peak flow rates of 20 athletes exercising at 181 W with minimal resistance to data on non-athletes in the same age group and to all non-athletes in their study. Peak inspiratory flow rates for athletes, age-matched non-athletes, and all non-athletes averaged 180 ± 30, 196 ± 29, and 205 L·min$^{-1}$, respectively. The peak flows were 10% lower for athletes compared to age-matched non-athletes.

Lafortuna *et al.* (82) investigated PIF rates for six males (mean age 27.5 ± 13.2 years) during rest and during incremental cycle ergometer exercise at 40, 80, 120, 160, and 200 W. Flow rates were measured with a No. 3 Fleisch pneumotachograph. Peak inspiratory flow rates were 36.6, 79.3, 104.8, 134.9, 184.5, and 238.7 L·min$^{-1}$ from rest to maximal exercise. Harber *et al.* (54) also investigated PIF rates during rest and exercise for six female and five male subjects between the ages of 22 and 39 years. This study involved a minimum of six minutes of steady state treadmill work, which continued until respiratory rate and heart rate stabilized for at least 60 seconds before measurements of flow were obtained with a pneumotachograph. The exercise levels were rest, low (0.89 mph, 0% grade), moderate (1.34 mph, 0% grade), high (1.34 mph, 10% grade), and maximal (1.7 mph, varied grade). The grade for maximal exercise was set to a level that the researchers estimated would exhaust the subject within several minutes. Each work rate was performed with and without a resistive load. Peak inspiratory flow rates for the no load condition from rest to maximum exercise were 40.8 ± 19.2, 68.4 ± 14.4, 88.8 ± 16.8, 135 ± 43.2, and 165 ± 46.8 L·min$^{-1}$, respectively.

Collectively, these observations show that PIF rates increase as exercise intensity increases and suggest that PIF rates on the order of 300 L·min$^{-1}$ are possible under heavy work conditions. Since PIF data is not commonly addressed in energy expenditure literature, PIF are often estimated by multiplying $\dot{V}E$ by the constant $\pi$ (3.14). This relationship assumes a sinusoidal breathing waveform, which is not a natural waveshape for inhalation when workloads exceed light intensities.(72) Sharkey and Gaskill (128) suggest that PIF can be adequately estimated by multiplying $\dot{V}E$ by a factor of four based on data presented by Silverman *et al.* (130) However, this relationship was determined from only one of the workloads utilized by Silverman *et al.* (130) and may cause significant overestimation of PIF at higher workloads when the ratio of PIF to $\dot{V}E$ decreases.(132) In addition, during unencumbered breathing, ratios of PIF to $\dot{V}E$ between five and six have been observed (K.M. Coyne, personal communication, February 27, 2004).

An alternate approach for estimating PIF from $\dot{V}E$ was attempted by determining the relationship between PIF and $\dot{V}E$ from data presented in Silverman *et al.* (130) and from data collected by Coyne (personal communication, February 27, 2004). These data, presented in Figure 2, demonstrated a significant ($p < 0.001$) linear relationship between $\dot{V}E$ and PIF with a coefficient of determination ($R^2$) of 0.82 in the form

$$PIF\,(\mathrm{L\cdot min^{-1}}) = 3.19\ \dot{V}E + 4.49 \qquad (5)$$

with $\dot{V}_E$ in L·min$^{-1}$. The 95% prediction interval for this regression was computed in order to estimate a potential range of PIF rates for a given $\dot{V}_E$. A prediction interval is often used when each *y* value in a fit is a single observation rather than an average (as in this analysis) and is useful for predicting, for a given *x*, the *y* value of the next experiment.(40, 150) Thus, by calculating the prediction interval, estimates of the upper and lower boundaries for PIF could be predicted for any given $\dot{V}_E$. This range would represent the PIF values that would have a 95% probability of containing the true PIF based upon the fit of the present data. In addition, the upper limit of the 95% prediction interval for this analysis represents the highest predicted values of PIF that would be expected.

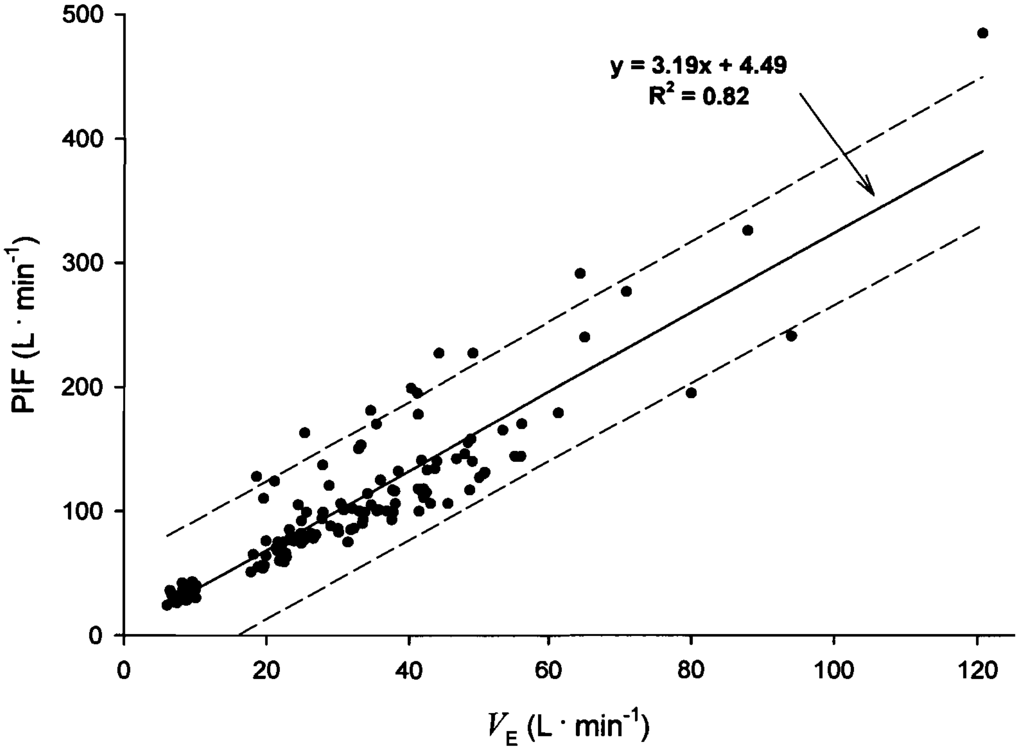

**Figure 2. Relationship of $\dot{V}_E$ and PIF Determined From Data Reported by Silverman *et al.* (130) and Coyne (Personal Communication, 2004). The Regression Line Represents the Linear Fit of the Values Reported From These Sources (i.e., Equation 5). The Shaded Area Represents the 95% Confidence Interval. The Dashed Lines are the Upper and Lower Ranges of the 95% Prediction Interval for the Data**

Figure 2 shows the linear regression and the 95% prediction interval for this analysis. The 95% confidence interval is also presented for comparison. The data derived from the analysis indicates the upper and lower boundaries of PIF rates estimated for $\dot{V}_E$ in the range of 6.1 L·min$^{-1}$ to 120.1 L·min$^{-1}$. An important distinction between the two types of intervals is that prediction intervals refer to observable quantities, such as future observations. Confidence intervals refer to parameters, such as probability, that cannot be observed, but still describe a process. Thus, if the goal were to describe the mean of a distribution, a confidence interval would be used. If the intent were to put a bound on the next observation from the distribution, a prediction interval would be described. It has been argued that prediction intervals tend to be too narrow because out-of-sample forecast accuracy is often poorer than would be expected from within-sample fit, particularly for prediction intervals calculated conditionally on a model fitted to past data.(23) However, the boundaries described by the prediction interval provide a broader range for estimates of PIF compared to the confidence interval.

In order to determine the validity of estimating PIF from $\dot{V}E$ based on the prediction interval for equation (5), we derived a range of PIF from the $\dot{V}E$ data reported by Silverman *et al.*,(131) Lafortuna *et al.*, (82) and Harber *et al.* (54) The derived values for PIF were then compared to average PIF data reported in conjunction with $\dot{V}E$. The results of this analysis showed that measured PIF values fell within the 95% prediction intervals derived from corresponding $\dot{V}E$ data 90% of the time. Measured PIF values that did not fit within the prediction interval were lower than the estimated range. For comparison, estimating PIF by multiplying reported $\dot{V}E$ data by a factor of four overestimated PIF values 86% of the time by an average of 59 $L{\cdot}min^{-1}$ (range from 8 to 169 $L{\cdot}min^{-1}$). These findings suggest that estimating ranges of PIF values from $\dot{V}E$ based on the prediction interval derived from the linear regression of equation (5) will produce adequate estimates of PIF rates. As demonstrated, values that fall outside of the prediction intervals are likely since the intervals are calculated on a model fitted to past data.

### 3.3 Speech Ventilation and PIF.

The main function of speech respiration is to provide the driving forces necessary to generate sounds. During speech breathing in healthy subjects the time spent on inspiration is minimized, the proportion of time spent on inspiration is reduced, and inspiratory flow rates are increased. Exhalation flow rates are either reduced or unchanged during speech production at rest.(125) In general, $f$ is reduced and $V_T$ is increased to accommodate the need for sustained speech-related exhalations with minimal disturbances in fluency. The flow dynamics of speech also vary based on the type of speech that is utilized (e.g., single words or connected utterances as in conversational speech, normal versus loud speech, etc.) and the physical activity level of the speaking individual.(25, 62, 63, 90, 117, 125, 153) A brief review of the ventilatory values anticipated during speech in healthy individuals is provided below. Unless otherwise noted, the data reported herein were gathered using RIP techniques, which appear to have wide acceptance for determination of speech ventilatory parameters.

Horii and Cooke (63) recorded PIF rates with a pneumotachograph in the range of 72 to 144 $L{\cdot}min^{-1}$ during about 2.5 minutes of continuous reading in a normal voice. Mean inspiratory flow rate ($V_T/T_I$) was approximately 66 $L{\cdot}min^{-1}$ and roughly only 13% of the speaking time was used for inspiration. Comparable $V_T/T_I$ values have been reported for oral monologue speech as well as for continuous conversational speech.(90) Horii and Cooke (63) also found that large inspiratory volumes were usually associated with inter-sentence inspirations, while smaller volumes were typically related to intra-sentence inspirations. On this point, there is general agreement that breaths are largely taken at places in text that are logical in terms of either punctuation or linguistic factors such as grammatical structure.(153)

Loudon *et al.* (90) reported an average $V_T/T_I$ of 76.9 ± 30.7 $L \cdot min^{-1}$ during oral counting while maintaining a speech intensity of 50 to 65 dB and an average $V_T/T_I$ of 108.8 ± 45.9 $L \cdot min^{-1}$ while maintaining a speech intensity of 80 to 95 dB. Using the linear relationship

$$PIF\ (L \cdot min^{-1}) = 1.41\ V_T/T_I\ (L \cdot min^{-1}) - 5.67 \qquad (6)$$

observed between PIF and $V_T/T_I$ from speech airflow data recorded in our laboratory ($R^2 = 0.92$, $p < 0.001$), corresponding PIF rates would be approximately 103 ± 38 $L \cdot min^{-1}$ and 148 ± 60 $L \cdot min^{-1}$ for the respective speech intensities. These findings show that utterances of single words and vocal intensity produce higher $V_T/T_I$ and PIF rates compared to those recorded during conversational speech in a normal voice. Minute volumes reported during speech at rest also appear to be impacted by vocal intensity, with higher rates found with greater output volumes.(125)

In general, speech during exercise has been associated with decreased $\dot{V}E$ while $V_T/T_I$ is held relatively constant.(113) With increasing levels of exercise, speech becomes more difficult, louder, and sometimes tremulous. The increased work intensities require significant increases in ventilation that cannot be maintained if interrupted or slowed by speech.(125) Doust and Patrick (33) tested the effect of five minutes of connected speech on ventilation during steady-state treadmill exercise at five different workloads. At each exercise level, $\dot{V}E$ was reduced during speech to about 55% of the non-speech $\dot{V}E$. Respiratory frequency was reduced but $V_T$ was relatively unchanged. Meckel *et al.* (102) also reported a significant reduction in $\dot{V}E$, as well as $\dot{V}O_2$, during speech while exercising at three different work intensities. Reductions in $\dot{V}E$ ranged from 24% to 10.5% during the lowest and highest work rates, respectively. Thus, speech during exercise appears to reduce ventilation so as to meet the phonatory requirements of low expiratory flow. Limited data for inspiratory flow patterns during speech and exercise were reported. Estimates of $V_T/T_I$ from Meckel *et al.* (102) suggest that mean inspiratory flows between 128 and 208 $L \cdot min^{-1}$ (with estimated PIF between 171 and 288 $L \cdot min^{-1}$) are likely when speech is produced during work intensities between 2.1 and 3.3 $L \cdot min^{-1}$ of oxygen consumption. However, the influences of speech characteristics such as intensity and content on these values are unknown under exercising conditions.

## 4. VENTILATION FOR SPECIFIC PHYSICAL ACTIVITIES

### 4.1 Ventilation Rates Recorded at Worksites or During Simulated Workplace Activities.

As mentioned previously, there is a shortage of data available for breathing flow rates and breathing patterns in actual occupational settings. However, some reports contain minute volume data collected during work or simulated task performance at worksites or in controlled settings. Smolander *et al.* (133) measured minute volumes of nine male city caretakers (mean age of 43 ± 10 years) during manual snow clearing, a task that all were accustomed to performing during their daily work. Minute ventilation was measured with a K-M respirometer during the last 10 minutes of two separate 15-minute self-paced snow clearing tasks (one with a shovel and one with a snow pusher) and averaged for each activity period. Smolander *et al.* (133) observed an average $\dot{V}E$ of 60.7 ± 11.3 L·min$^{-1}$ during snow shoveling and an average $\dot{V}E$ of 65.8 ± 11.3 L·min$^{-1}$ during snow pushing. Using on-line indirect calorimetry, Bridger *et al.* (17) found similar ventilation rates in a controlled laboratory study for individuals (10 males, 25 ± four years of age) shoveling sand with either a conventional shovel ($\dot{V}E$ = 64.1 ± 16.1 L·min$^{-1}$) or a two-handled shovel ($\dot{V}E$ = 63.5 ± 13.6 L·min$^{-1}$) at a controlled pace for approximately 12 minutes. The oxygen consumption data from both Smolander *et al.* (133) and Bridger *et al.* (17) were also similar, indicating that the work intensities were the same between the simulated workplace shoveling tasks and the controlled laboratory tasks. Both investigations show that shoveling is strenuous physical work that elicits a relatively high level of ventilation. Since digging and shoveling are common tasks in a range of industries as well as in leisure activities such as gardening, $\dot{V}E$ levels on the order of magnitude found by Smolander *et al.* (133) and Bridger *et al.* (17) should be considered to be normal occurrences in similar manual labor activities.

Gallagher and Hamrick (46) recorded minute ventilation data on 12 male subjects (approximately 42 years old) during a series of lifting studies designed to simulate lifting tasks and postures commonly performed in underground coal mines. All subjects were current or former coal miners experienced with handling materials in underground mines. The range of average minute volumes measured with a metabolic cart was approximately 21 to 27 L·min$^{-1}$ for the various container types and lifting postures tested and the weights of the lifted loads (20 - 24 kg). The physiological workloads ($\dot{V}O_2$) ranged between 0.82 L·min$^{-1}$ to 1.04 L·min$^{-1}$ (9.8 to 12.7 mL·kg$^{-1}$·min$^{-1}$) for all tasks, which can be categorized as moderate work (Table 1). Although these data were collected in a simulated environment, the lifting weights assessed were self-selected by the subjects according to their own estimate of an acceptable lifting capacity and workload for each 15 minute treatment session. In addition, vertical space constraints for stooped lifting postures were controlled with a device that was adjusted to mimic underground mine ceiling heights. Since underground lifting tasks are often less than 10 minutes in duration, with ample breaks in between,(45) the data reported by Gallagher and Hamrick (46) provide reasonable estimates of $\dot{V}E$ that would be found during short duration, sporadic lifting tasks common in underground mining occupations.

Linn *et al.* (89) estimated ventilation rates of 19 construction workers throughout a day on the job including some time before work and breaks. These investigators calibrated each individual by recording heart rate and $\dot{V}E$ at rest and at different levels of exercise. Least squares regression analysis was used to derive an equation predicting $\dot{V}E$ at a given heart rate for each subject. The subjects' heart rates were subsequently recorded beginning early in the morning at home and ending in the afternoon when the subjects stopped working. A diary of the subjects' activities was also kept, with each subject recording from waking to getting to work and a trained investigator entering information as communicated by the subject via a hands-free transmitter during work. Each individual's $\dot{V}E$ prediction equation was used to calculate $\dot{V}E$ from the recorded HR data. For the 19 subjects, a total of 182 hours of heart rate data was recorded, of which 144 hours represented actual work time. The construction workers estimated $\dot{V}E$ ranged from about 20 L·min$^{-1}$ to 44 L·min$^{-1}$ and averaged 30 L·min$^{-1}$. These findings indicate that the job-site construction work assessed involved moderate to strenuous amounts of work (Table 1).

However, it is possible that this data may have underestimated $\dot{V}_E$ during construction work activities. First, the ventilation data in the Linn *et al.* (89) study included time off work that could not be adequately accounted for when estimating $\dot{V}_E$ during actual working periods. In addition, others have shown that predicting $\dot{V}_E$ from heart rate data in uncontrolled settings generally leads to lower estimates of $\dot{V}_E$.(1, 12, 104) Therefore, the precision of the $\dot{V}_E$ data reported by Linn *et al.* (89) is somewhat limited and may not be the best representation for ventilation rates common to construction work. In this regard, the data from Linn *et al.* (89) are presented herein as a representation of worksite recordings of $\dot{V}_E$ and for later comparison with like activities.

The California Air Resources Board (CARB) sponsored a study in 1993 of measured ventilation rates in people performing various laboratory and field protocols.(1) Subjects completed resting and exercise protocols in the laboratory, and usually one or more field activities. Data collected in the field included $\dot{V}_E$, heart rate, and $f$ during housework, yard work, car riding and driving, car maintenance, and woodworking activities. Car riding and driving protocols were 20 minutes long; the others were 30 minutes long. A wide variation in individual intensity of effort across subjects in the field protocols was noted. The mean $\dot{V}_E$ values presented in Table 3 indicate that ventilation rates during the various activities corresponded to relatively mild to moderate intensity workloads. Both car driving and car riding can be classified as resting activities.

**Table 3. Mean Values for Ventilation ($\dot{V}_E$) by Group Measured During Activities Assessed by Adams (1)**

| Activity | Females ($L \cdot min^{-1}$) | Males ($L \cdot min^{-1}$) |
|---|---|---|
| **Car driving** | 9.0 | 10.8 |
| **Car riding** | 8.2 | 9.8 |
| **Car maintenance** | | 23.2 |
| **Yard work** | 19.2 | 26.3 |
| **Mowing** | | 36.6 |
| **Housework** | 17.4 | |
| **Woodworking** | | 24.4 |

Spurr *et al.* (137) measured $\dot{V}_E$ in 28 sugarcane loaders working in pairs to manually load cane, an intermittent task done with intensity as wagons were available for loading. The loading of cut sugarcane was accomplished by picking up stalks of cut cane (1 to 2 kg each), either singly or in small bundles, and throwing them on the wagon (maximum load height of about 5 meters). Minute volumes were measured during the 15th, 30th, and 45th minute of the loading task using K-M respirometers. Minute volumes recorded during each measurement period were statistically similar, indicating that the cane-loading task involved a steady level of work. Independent of measurement period, $\dot{V}_E$ averaged $38.8 \pm 6.8$ $L \cdot min^{-1}$ for the cane loading task. The average time to completely load a wagon was 58 ± 16 min and the average $\dot{V}O_2$ was $1.3 \pm 0.2$ $L \cdot min^{-1}$.

These results provide reference values of $\dot{V}_E$ for a moderate effort (Table 1), intermittent lifting task.

In contrast to the material handling studies already discussed,(46, 137) Mackey *et al.* (99) quantified breathing patterns of 10 females (31.8 ± 6.2 years old) during a simulated upper body work task designed to mimic small materials handling and inspection work. Minute volumes were measured with a pneumotachograph while subjects performed the simulated work task when seated, once with the arms in a supported position (both elbows resting on a work bench) and once with the arms unsupported during the inspection phase of the task. The simulated task required subjects to repeatedly pick up a 2 kg object, inspect and hold it for 15 seconds, and place it in a box for five minutes. Minute volumes averaged 14.8 $L \cdot min^{-1}$ during unsupported arm work and 13.4 $L \cdot min^{-1}$ when the arms were supported. The difference between $\dot{V}_E$ for the unsupported and supported arm conditions was statistically significant ($p < 0.01$). These findings provide values of $\dot{V}_E$ representative of occupational tasks that require repetitive material handling accomplished primarily with the arms.

Data collected during emergency egress simulations provide insight into ventilation rates that can occur during physically demanding emergency situations. Kamon *et al.* (76) measured $\dot{V}_{O_2}$ and $\dot{V}_E$ during a simulated escape from an underground mine that was completed by six miners (mean age 45.2 ± 13.6 years) asked to perform the escape maneuver "as rapidly as they possibly could." The escape route included sections of different terrain and roof heights, which required periods of upright and head-bent walking, duck walking, running, and crawling. Minute ventilation, measured with an Oxylog, averaged 49 ± 13 $L \cdot min^{-1}$ throughout the escape route for all subjects. The average of peak $\dot{V}_E$ recorded at any time for all subjects was 56 ± 13 $L \cdot min^{-1}$. The mean travel time for the six miners was 58 minutes. In a much shorter exercise (5.4 to 6.7 minutes), Ross *et al.* (124) recorded average minute volumes of 46.3 ± 15.8 $L \cdot min^{-1}$ in 26 offshore oil industry workers (mean age of 36.7 years) during a simulated escape from an offshore oil installation. Peak $\dot{V}_E$ values ranged from approximately 31 to 87 $L \cdot min^{-1}$ over the duration of the exercise. The data gathered in these two investigations are comparable and indicate that high ventilation rates are likely during life-threatening emergency escape situations.

### 4.2 Estimates of Ventilation From Energy Expenditure Studies.

The vast majority of workplace and simulated workplace studies designed to quantify energy expenditures of various tasks focus more on measurements of energy expenditure and work rates as opposed to ventilation. Therefore, much of the data reported in these investigations is void of minute volume data, even when minute volumes were collected during testing. In such cases, where measurements of oxygen consumption were presented, the equations provided by both Baba *et al.* (10) and Hagan and Smith (51) were utilized when applicable to estimate minute volumes for occupational task performance when ventilation data were not reported.

In a study analogous to that of Smolander *et al.*,(133) Franklin *et al.* (43) measured cardiorespiratory responses to self-paced snow removal in 10 apparently healthy, untrained men (mean age 32.4 ± 2.1 years). Test participants cleared heavy, wet snow with either a shovel or an electric snow thrower in random order, with 10- to 15-minute rest periods between each 10-minute work period. Oxygen consumption, measured during the last four minutes of each work task with a portable TEEM 100 Metabolic Analysis System and expressed as metabolic equivalents (METs; 1 MET = 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$) averaged 5.7 ± 0.8 METs for shoveling and 2.4 ± 0.7 METs with the automated snow thrower. Using the average subject population weight of 85.7 kg, estimated $\dot{V}_{O2}$ in $L \cdot min^{-1}$ would be about 1.71 $L \cdot min^{-1}$ for shoveling and 0.72 $L \cdot min^{-1}$ for automated snow removal based on the equation

$$\dot{V}_{O2}\ (L \cdot min^{-1}) = EE \cdot 3.5\ mL \cdot kg^{-1} \cdot min^{-1} \cdot BW/1000 \qquad (7)$$

where: EE= energy expenditure (METs)

BW = body weight (kg)

For these levels of $\dot{V}_{O2}$, estimates of $\dot{V}_E$ during manual shoveling are 39.2 $L \cdot min^{-1}$ and 61.1 $L \cdot min^{-1}$ using the Hagan and Smith (51) and Baba *et al.* (10) equations, respectively (Table 4). The estimate of $\dot{V}_E$ based on the exponential function of Baba *et al.* (10) is comparable to the measured minute volumes during snow shoveling reported by Smolander *et al.*(133) The estimate of $\dot{V}_E$ during automated snow removal is 26.6 $L \cdot min^{-1}$ based solely on the Baba *et al.* (10) relationship; the Hagan and Smith (51) equation was not applicable to this activity because the estimated $\dot{V}_{O2}$ was less than 0.9 $L \cdot min^{-1}$.

Hagen *et al.* (52) recorded $\dot{V}_{O2}$ data from 31 woodcutters performing on the job motor-manual wood cutting tasks (i.e., using a chainsaw) for an average work period of 111 ± 21 minutes. Oxygen consumption was measured during the last 30 minutes of each working shift with an Oxylog system. The work periods included felling, limbing, manual hauling of wood, walking, and chainsaw maintenance, as well as intermittent delays. The mean $\dot{V}_{O2}$ during work for the younger subject group (28.5 ± 3.9 years, n = 15) was 1.8 ± 0.2 $L \cdot min^{-1}$. Minute volume estimates for this level of $\dot{V}_{O2}$ fall between 41.1 $L \cdot min^{-1}$ and 65.9 $L \cdot min^{-1}$. Based on an average $\dot{V}_{O2}$ of 1.5 ± 0.2 $L \cdot min^{-1}$, anticipated minute volumes for the older subject population (58.5 ± 5.1 years, n = 16) would be from 35.2 $L \cdot min^{-1}$ to 51.2 $L \cdot min^{-1}$ (Table 4). The mean $\dot{V}_{O2}$ during work for all working phases for both age groups was 1.7 ± 0.3 $L \cdot min^{-1}$, which equates to estimated minute volumes of 39.0 $L \cdot min^{-1}$ to 60.6 $L \cdot min^{-1}$.

In a similar assessment of the physical demands of forestry operations performed by six male forestry workers (51 ± 6 years of age), Kurumatani *et al.* (81) estimated energy expenditures for multiple tasks from the average heart rate during the activity of interest and a predicted maximal oxygen consumption of the subject obtained from a submaximal cycle ergometer test. Metabolic rates expressed in METs were converted to $\dot{V}_{O2}$ values ($L \cdot min^{-1}$) using the mean body weight of the test subject population and equation (7) so that estimates of $\dot{V}_E$ could be calculated. The estimated minute volumes for four of the tasks assessed by Kurumatani *et al.* (81) are presented in Table 4. Despite the similarities in the tasks assessed by Kurumatani *et al.* (81) and Hagen *et al.*,(52) the estimates of $\dot{V}_E$ were lower for the subject population assessed by Kurumatani *et al.* (81) when compared with the older, age-matched subject group in the work of Hagen *et al.*(52) Given that $\dot{V}_E$ is positively correlated with body weight,(7, 12) the lower minute volumes found by Kurumatani *et al.* (81) were likely due to the lower weight of their subject population compared to Hagen *et al.*(52) Nevertheless, these findings demonstrate the variety in energy expenditure rates and, thus $\dot{V}_E$, that can be found for similar activities due to individual variability of the worker population.

**Table 4. Estimated Minute Volumes Based on Oxygen Consumption Data Obtained From Select Energy Expenditure Publications**

| Reference | Job Task(s) | Mean $\dot{V}O_2$ (L·min$^{-1}$) | Estimated $\dot{V}_E$ (L·min$^{-1}$) Hagan & Smith | Estimated $\dot{V}_E$ (L·min$^{-1}$) Baba et al. |
|---|---|---|---|---|
| Franklin *et al.* (1995) | Manual snow shoveling | 1.71 | 39.2 | 61.1 |
| | Automated snow removal | 0.72 | | 26.6 |
| Hagen *et al.* (1993) | Wood-cutting (young group) | 1.8 | 41.1 | 65.9 |
| | Wood-cutting (older group) | 1.5 | 35.2 | 51.2 |
| Kurumatani *et al.* (1992) | Felling trees | 1.09 | 28.5 | 36.2 |
| | Limbing & bucking | 0.99 | 27.0 | 33.2 |
| | Dragging logs w/peavey | 1.05 | 27.9 | 35.0 |
| | Walking | 1.03 | 27.6 | 34.4 |
| Aminoff *et al.* (1999) | Kitchen work | 0.65 | | 22.7 |
| Wakui *et al.* (2002) | Nursing home care (day shift) | 0.52 | | 21.3 |
| | Nursing home care (night shift) | 0.55 | | 21.6 |
| Ahonen *et al.* (1990) | Giving fresh hay | 1.36 (1.28)[a] | 32.8 (31.4) | 45.6 (42.5) |
| | Milking | 0.84 (0.86) | | 29.5 (29.9) |
| | Removing manure | 1.26 (1.09) | 31.2 (28.5) | 41.9 (36.2) |
| | Cleaning floor | 1.09 (0.91) | 28.5 (26.0) | 36.2 (31.2) |
| Gunn et al. (2002) | Walking | 1.05 | 27.9 | 35.1 |
| | Sweeping | 0.90 | 25.9 | 30.9 |
| | Window cleaning | 1.00 | 27.3 | 33.7 |
| | Vacuuming | 0.79 | | 28.1 |
| | Mowing | 1.39 | 33.4 | 46.9 |
| Ilmarinen (1984) | Carrying/stacking steel rods | 2.00 | 45.6 | 78.1 |
| | Working with a wheelbarrow | 1.50 | 35.2 | 51.2 |
| Lemon and Hermiston (1977) | Ladder climbing | 2.19 | 50.3 | 91.6 |
| | Victim rescuing | 2.53 | 59.9 | |
| | Hose dragging | 2.55 | 60.5 | |
| | Ladder raising | 2.30 | 53.2 | |
| Sothmann et al. (1992) | Emergency firefighting | 2.28 | 52.6 | |

[a] Data in parentheses is for female test participants

Aminoff *et al.* [(5)] recorded performance data from nine hospital kitchen workers (six females and three males) while working 30 minute shifts at a conveyer belt collecting and sorting dishes for cleaning. The work movements involved twisting from right to left as subjects collected the plates and glassware, emptied leftovers from them, and put them in washing baskets. Physiological responses were measured continuously for each subject with a portable system (Cosmed K4). No differences in $\dot{V}O_2$ were observed between the male and female subjects. The mean $\dot{V}O_2$ for all subjects during work was 0.65 L·min$^{-1}$. Despite the fact that the Cosmed K4 system measures and records $\dot{V}_E$, these data were not reported. The anticipated ventilation rate associated with this level of work intensity using the Baba *et al.* (10) equation is 22.7 L·min$^{-1}$ (Table 4). It should be noted that the $\dot{V}_E/\dot{V}O_2$ for this estimated minute volume is approximately 35, which is considered to be rather high for a task that would be classified as light work. However, the work tasks of this study involved primarily upper body activities, which utilized a relatively small active muscle mass for completion. It has been documented that ventilation at a given level of oxygen consumption is greater when activities involve primarily small muscle groups (e.g., the arms) than it is when larger muscle groups (e.g., leg muscles) are utilized.(8) Likewise, Mackey *et al.* (99) demonstrated that $\dot{V}_E$ is significantly lower during supported arm work (e.g., with elbows resting on a surface) than during unsupported arm work like that involved in the kitchen work described by Aminoff *et al.*(5)

Another investigation that assessed job-related work intensities was reported by Wakui *et al.* (145) who examined energy expenditure and work rates of female nursing home care providers by monitoring heart rates over time. The types of work activities that were assessed included assisting nursing home residents with feeding, bathing, using the rest room, movement, and dressing, as well as administrative duties. Data were collected for subjects during day shift work (approximately nine hours) and night shift work (approximately 16 hours). Break times were not included in the data analysis. Oxygen uptake during care work was calculated for each subject based on the heart rate-oxygen uptake regression equation developed for each individual and energy expenditures were determined by multiplying $\dot{V}O_2$ (L·min$^{-1}$) by 5 kcal. Thus, the energy expenditures reported by Wakui *et al.* (145) were reconverted to rates of oxygen consumption so that estimates of $\dot{V}_E$ could be calculated. The estimated $\dot{V}_E$ for nursing care providers ranged from approximately 21 L·min$^{-1}$ to 23 L·min$^{-1}$ for both day and night shift workers. Since $\dot{V}O_2$ levels were well below 0.9 L·min$^{-1}$, estimates of $\dot{V}_E$ are based solely on the exponential function of Baba *et al.*(10) It is likely that instances of higher and lower breathing rates occurred during the working hours assessed in this study, but the researchers reported only average energy expenditure data for each working shift.

Estimates of ventilation for tasks performed in an agricultural setting were derived from data reported by Ahonen *et al.* (2) who measured $\dot{V}O_2$ of both male and female dairy farmers during various short-term work tasks. Oxygen consumption data were obtained using an Oxylog. The estimated $\dot{V}_E$ values for some of the common tasks in dairy farming reported by Ahonen *et al.* (2) are presented in Table 4. For the male farmers, the estimated $\dot{V}_E$ data were recorded over task durations that averaged between five and 12 minutes, whereas the same tasks were about three to 16 minutes in duration for the females. The handling of feed was the heaviest work task assessed, which produced average $\dot{V}O_2$ values of 1.36 L·min$^{-1}$ for males and 1.28 L·min$^{-1}$ for females, indicating that the task was moderate intensity work (Table 1). Corresponding $\dot{V}_E$ estimates for these workloads are 32.8 L·min$^{-1}$ to 45.6 L·min$^{-1}$ for males and 31.4 L·min$^{-1}$ to 42.5 L·min$^{-1}$ for females.

Gunn *et al.* (50) reported the energy costs associated with doing some household and gardening tasks for 12 men (38 ± 4 years) and 12 women (39.9 ± 3 years) using the Douglas bag technique to collect respired gases. Respired air volumes were measured with a spirometer. Oxygen consumption was recorded for the following tasks: a) self-determined moderate paced walking; b) sweeping and lawn mowing (push-power mower); c) window cleaning and self-paced vacuuming. The metabolic data did not differ between men and women for any of the activities so the data were combined. The estimated $\dot{V}_E$ data based on the average $\dot{V}_{O_2}$ data reported by Gunn *et al.* (50) are presented in Table 4. The estimated ranges of minute volumes are approximately 23 to 47 L·min$^{-1}$ for moderate paced walking (average speed of 5 km·hr$^{-1}$), 23 L·min$^{-1}$ to 39 L·min$^{-1}$ for sweeping, 23 L·min$^{-1}$ to 45 L·min$^{-1}$ for window cleaning, 21 L·min$^{-1}$ to 36 L·min$^{-1}$ for vacuuming, and 27 L·min$^{-1}$ to 65 L·min$^{-1}$ for lawn mowing. In a comparative test using a subset of healthy older males (mean age of 74 years) and females (mean age of 64 years), Sheldahl *et al.* (129) reported lower average $\dot{V}_{O_2}$ data during mowing with a motorized push mower. Even so, estimated levels of $\dot{V}_E$ (roughly 28 L·min$^{-1}$ to 38 L·min$^{-1}$) were within the range recorded by Gunn *et al.*(50) Combined with the $\dot{V}_E$ data reported by Adams (1) collected during mowing (Table 3), these findings suggest that the estimates from the energy expenditure data are reasonable for lawn mowing tasks.

Ilmarinen (66) cites limited construction work $\dot{V}_{O_2}$ values in excess of 2 L·min$^{-1}$ during tasks involving carrying and stacking steel rods and 1.5 L·min$^{-1}$ for various wheelbarrow loading, pushing, and unloading tasks. Oxygen consumption rates in the steel industry were reported to be "somewhat lower" than in construction work but empirical data were not provided. These rates of oxygen uptake suggest that minute volumes in the range of 35 L·min$^{-1}$ to 78 L·min$^{-1}$ are likely to occur in these occupational settings (Table 4). Compared to the observations of Linn *et al.*,(89) these estimates of $\dot{V}_E$ are somewhat higher, a finding that may be attributed to the methods that were used to predict $\dot{V}_E$ from heart rate responses. Nevertheless, as a whole, the estimates of $\dot{V}_E$ based on $\dot{V}_{O_2}$ values cited by Ilmarinen (66) and the findings of Linn *et al.* (89) suggest that a wide range of ventilation rates are likely for construction work activities.

Researchers that have analyzed the physical demands of firefighting indicate that firefighting consists of heavy physical work.(49, 86, 98, 135) Considering that many of the tasks required of firefighters are difficult to assess during real emergencies, much of the literature addresses the energy costs of fire fighting during simulated activities. Lemon and Hermiston (86) measured $\dot{V}_{O_2}$ in 23 firefighters (23 to 43 years old) participating in four simulated work tasks (ladder climb, victim rescue, hose drag, and ladder raise) using the Douglas bag method. The ladder-climbing task was completed in 100 seconds whereas each of the remaining tasks were performed for 30 seconds. Mean $\dot{V}_{O_2}$ values for the four tasks were between approximately 2.2 and 2.6 L·min$^{-1}$. Thus, the estimated ventilation rates for the tasks assessed by Lemon and Hermiston (86) range anywhere between 50 L·min$^{-1}$ and 92 L·min$^{-1}$ (Table 4).

Using heart rate and oxygen consumption relationships established for 10 individual firefighters, Sothmann *et al.* (135) estimated mean $\dot{V}_{O_2}$ values of 25.6 ± 8.7 mL·kg$^{-1}$·min$^{-1}$ (approximately 2.28 ± 0.78 L·min$^{-1}$ based on a mean population body weight of 89 kg) from heart rate monitoring in actual fire emergencies. An estimate of $\dot{V}_E$ for an average $\dot{V}_{O_2}$ of 2.28 L·min$^{-1}$ is approximately 53 L·min$^{-1}$, which is comparable to estimates derived from the firefighting simulations assessed by Lemon and Hermiston.(86) Furthermore, the estimates of $\dot{V}_E$ provided for firefighting are comparable to the $\dot{V}_E$ data gathered during simulated escape exercises reported by Kamon *et al.* (76) and Ross *et al.*,(124) which are comparable emergency activities requiring heavy physical work. Therefore, it is apparent that firefighting is strenuous work that necessitates high levels of ventilation to meet metabolic demands.

Physical activity data from two additional documents were utilized to estimate ventilation rates from metabolic rates representative of occupational activities. The International Organization for Standardization (ISO) Standard 8996 titled "Ergonomics – Determination of metabolic heat production" contains metabolic rates for various work and leisure activities that were derived using oxygen consumption and heart rate data from multiple sources.(68) The ISO 8996 standard presents metabolic rates in units of $W \cdot m^{-2}$. Using information published in the standard, ISO metabolic rates were converted into units of $\dot{V}_{O2}$ ($L \cdot min^{-1}$) with the assumption that the energy equivalent of oxygen was 5 kcal per liter of oxygen consumed using the equation

$$\begin{aligned} \dot{V}_{O2} &= \frac{M \cdot A_{Du}}{60 \cdot (5.815)} \\ &= \frac{M \cdot A_{Du}}{348.9} \end{aligned} \tag{8}$$

where: $\dot{V}_{O2}$ = oxygen consumption ($L \cdot min^{-1}$)
M = ISO metabolic rate ($W \cdot m^{-2}$)
$A_{Du}$ = Dubois body surface area ($m^2$)
60 = conversion factor
5.815 = energy equivalent of oxygen ($W\text{-}hr \cdot L^{-1}\ O_2$)

Assuming a body surface area of 1.8 $m^2$ for males, the conversion equation is simplified to

$$\dot{V}_{O2} = \frac{M}{193.8} \tag{9}$$

and for females with a body surface area of 1.6 $m^2$ the equation is

$$\dot{V}_{O2} = \frac{M}{218.1} \tag{10}$$

After conversion of metabolic rates for occupational activities listed in ISO 8996 were accomplished by applying equations (9) and (10), estimates of ventilation for the occupational activities were again derived based on the exponential relationships of $\dot{V}_E$ and $\dot{V}_{O2}$ as presented earlier. The results of this analysis are presented in the Appendix. Estimates of $\dot{V}_E$ for females were included in the analysis to demonstrate the differences in ventilation between males and females. Gender differences in flow rates have been previously documented and indicate that females typically have lower $\dot{V}_E$ at rest and during exercise, particularly with maximal efforts.(4, 15, 79)

The data in Tables A.1 and A.2 show mean values of metabolic rates for the duration of a working period for certain occupations without considering rest periods. Thus, significant variation in work rates and $\dot{V}_E$ should be expected due to differences in a worker's cardiovascular health as well as differences in technology, work tasks, work organization, etc. The estimates of $\dot{V}_E$ presented in Tables A.1 and A.2 were derived solely from the exponential $\dot{V}_E$ to $\dot{V}_{O_2}$ relationship of Baba *et al.* (10) because all $\dot{V}_{O_2}$ values were below the minimum range (0.9 $L \cdot min^{-1}$) of the Hagan and Smith (51) equation. This analysis indicates that mean ventilation rates for the occupations listed generally fall between 20 $L \cdot min^{-1}$ and 40 $L \cdot min^{-1}$.

Table A.3 presents metabolic rates measured during specific occupational activities selected from ISO Standard 8996 and our estimates of $\dot{V}_E$ for the various tasks based on work rates using both the Hagan and Smith (51) and Baba *et al.* (10) functions where applicable. The data presented in Table A.3 permits cursory comparisons with both measured and estimated $\dot{V}_E$ for certain work activities. For example, as previously detailed, we estimated $\dot{V}_E$ values in the range of roughly 29 $L \cdot min^{-1}$ to 66 $L \cdot min^{-1}$ for chainsaw wood-cutting activities based on the reports of Hagen *et al.* (52) and Kurumatani *et al.*(81) According to the metabolic rates listed for like activities in Table A.3 (i.e., "felling with power saw" and "cutting across the grain"), estimates of $\dot{V}_E$ fall between 27 $L \cdot min^{-1}$ and 40 $L \cdot min^{-1}$ (males) and are in general agreement with our estimates from Hagan *et al.* (51) and Kurumatani *et al.*(81) Likewise, Table A.3 $\dot{V}_E$ estimates for "digging with spade" (45 $L \cdot min^{-1}$ to 76 $L \cdot min^{-1}$ (males)) are comparable to $\dot{V}_E$ estimates for snow shoveling based on the energy expenditure data from Franklin *et al.* (43) as well as from the measured $\dot{V}_E$ data reported by Smolander *et al.* (133) and Bridger *et al.* (17) for shovel work. These findings indicate that the estimates of $\dot{V}_E$ derived from the metabolic data presented in Table A.3 are adequate representations of the listed occupational activities. However, it is important to remember that individual differences in metabolic rates for the same activity can be large and the true energy cost for an individual may or may not be close to the metabolic rates presented in Table A.3. In this same context, variations in $\dot{V}_E$ should also be expected.

The Compendium of Physical Activities (3) provides an additional listing of physical activities performed in various settings with their respective metabolic equivalent (MET) intensity levels. As already mentioned, 1 MET is equivalent to 3.5 mL $O_2$ $kg^{-1} \cdot min^{-1}$ and is considered to be a resting metabolic rate obtained during quiet sitting. Activities are presented in the Compendium as multiples of the resting MET level. The Compendium has received widespread acceptance among physical activity specialists and has been cited as a reference that clinicians and practitioners can use to identify examples of moderate physical activities for exercise prescription. The Compendium was not developed to determine precise energy costs of physical activity within individuals, but instead to provide an activity classification system that standardizes the MET intensities of physical activities used in survey research.(3) However, since the MET levels listed for various activities in the Compendium are based on reported energy costs of published research (obtained both with and without indirect calorimetry), the data were considered to be useful for the purposes of this investigation, particularly since energy costs of multiple occupational activities are provided.

Table A.4 lists the physical activity codes and MET intensities for all of the activities classified under occupational activities. In order to estimate ventilation rates for the multiple tasks, MET levels were converted into oxygen consumption rates (L·min$^{-1}$) using equation (7) and assumed body weights of 75 kg and 60 kg for males and females, respectively. Again, as was evident with the $\dot{V}_E$ data presented in Table A.3, the $\dot{V}_E$ estimates derived from MET values from the Compendium of Physical Activities provided ventilation rates comparable to those previously presented for like activities. As one example, estimates of $\dot{V}_E$ for "farming, milking by hand, moderate effort" (Code 11210) listed in Table A.4 are 28.1 L·min$^{-1}$ for males and 24.6 L·min$^{-1}$ for females, numbers that match previous estimates of 25.1 L·min$^{-1}$ and 25.4 L·min$^{-1}$ for males and females based on metabolic data reported by Ahonen *et al.* (2) for the same activity. As was found for data from ISO Standard 8996, Table A.4 $\dot{V}_E$ estimates for "shoveling, digging ditches" and "shoveling, heavy" (Codes 11540 and 11550; 51.3 L·min$^{-1}$ and 54.9 L·min$^{-1}$ for males) are comparable to $\dot{V}_E$ estimates for snow shoveling based on the energy expenditure data from Franklin *et al.* (43) as well as from the measured $\dot{V}_E$ data reported for shovel work (17, 133). Therefore, it again appears that the estimates of $\dot{V}_E$ derived from the metabolic data provided by the Compendium of Physical Activities (Table A.4) are adequate representations of the occupational activities that are listed, keeping in mind that individual differences in metabolic rates for the same activity are likely and that variations in $\dot{V}_E$ are probable.

### 4.3 Summary of Measured and Estimated Ventilation Rates for Occupational Tasks.

The range and distribution of $\dot{V}_E$ measured or estimated from our review of the literature is presented in Figure 3. These data include reported mean $\dot{V}_E$ values for workplace and simulated workplace activities, $\dot{V}_E$ values estimated from reported mean energy expenditure rates from like studies using both the Hagan and Smith (51) and Baba *et al.* (10) relationships of $\dot{V}_E$ and $\dot{V}O_2$, and $\dot{V}_E$ estimates based on energy expenditure rates listed in Tables A.3 and A.4 from both ISO Standard 8996 (68) and the Compendium of Physical Activities.(3) The data for both male and female subjects were combined for this analysis.

Analysis of the data showed a positively skewed distribution for the $\dot{V}_E$ data, primarily due to the single outlying value of 162 L·min$^{-1}$. The mean $\dot{V}_E$ of the distribution was 38.5 ± 16.6 L·min$^{-1}$ (the peak of the normal distribution curve in Figure 3) and the median was 33.6 L·min$^{-1}$. The 95th percentile for $\dot{V}_E$ was 73.3 L·min$^{-1}$ indicating that only 5% of the measured or estimated minute volumes were above 73.3 L·min$^{-1}$. Based on the earlier discussion concerning prediction of PIF rate ranges, peak flows between 72 L·min$^{-1}$ and 183 L·min$^{-1}$ would be expected for the mean $\dot{V}_E$ of 38.5 L·min$^{-1}$. The anticipated range of PIF rates for the 95th percentile $\dot{V}_E$ is between 182 L·min$^{-1}$ and 295 L·min$^{-1}$, whereas peak flows between 457 L·min$^{-1}$ and 586 L·min$^{-1}$ are anticipated for the extreme $\dot{V}_E$ estimate of 162 L·min$^{-1}$. However, there are two factors that minimize the reliability of the PIF data estimated for the 162 L·min$^{-1}$ $\dot{V}_E$. First, the $\dot{V}_E$ value does not fit within the range of $\dot{V}_E$ data used to determine the 95% prediction interval (i.e., 6.1 L·min$^{-1}$ to 120.1 L·min$^{-1}$). Second, considering that $\dot{V}_E$ values of this extreme occur infrequently and appear to be attainable only for extremely well conditioned individuals performing maximal exercise,(9, 24, 55, 96, 97) it is likely that PIF rates on the order of nearly 600 L·min$^{-1}$ would be a rare occurrence in the workplace.

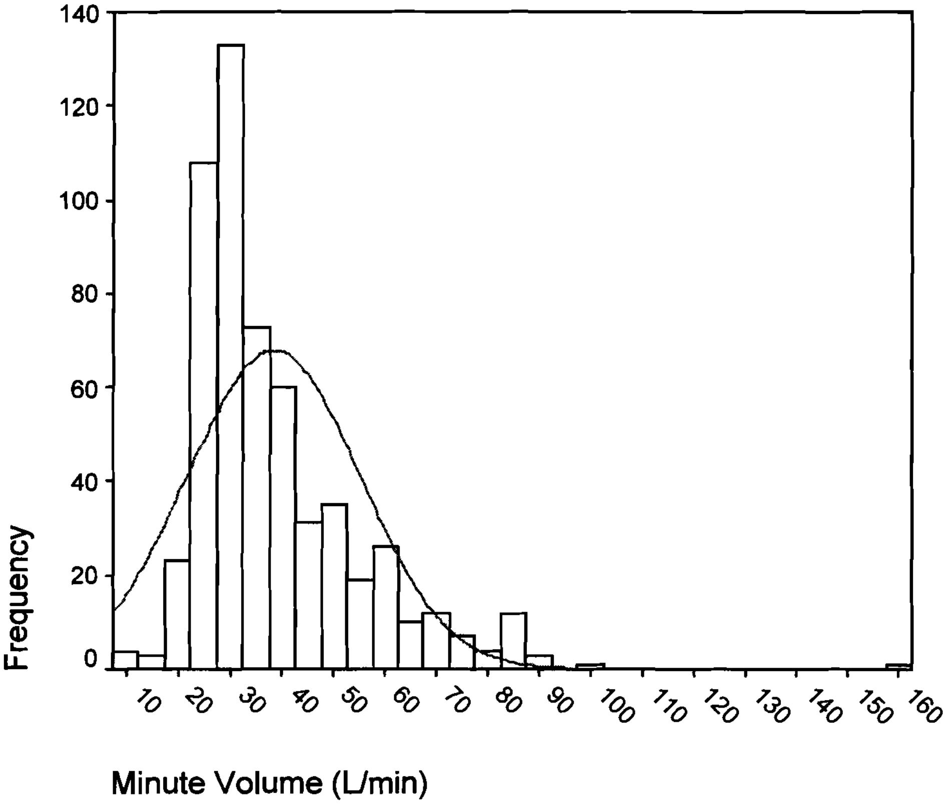

**Figure 3. Distribution of Ventilation Rates Measured or Estimated from Occupational Activity Literature Fitted with a Normal Distribution**

## 5. VENTILATION WITH IMPOSED BREATHING RESISTANCE

External ventilatory loads have been imposed on subjects in numerous studies to simulate respiratory system disorders. Even though resistive loading is not completely analogous to internal respiratory loading induced by airway diseases, it has been used as a mechanism to characterize the compensatory responses of the ventilatory system. Adding external ventilatory loads has also served to simulate respirator resistance breathing and many investigators have examined the impact of respirator wear on human performance. Unfortunately, non-uniformity in the levels of externally applied resistive loads, as well as subject populations and workloads utilized to gauge their effects, prevents simple development of acceptable breathing resistances for respirator design and use. How external ventilatory loads are applied may also impact human ventilatory responses.(32, 138) A general review of the impacts of applied resistive loads both with and without respirators follows. The purpose of this review is to highlight the primary effects of resistive load breathing on ventilation.

### 5.1 Non-Respirator Applied Resistive Breathing Loads.

In response to external resistive loading, the pattern of breathing changes rather consistently for both inspiratory resistive loads (IRL) and expiratory resistive loads (ERL) with inter-individual differences in the amount of these changes. Under resting conditions, there is general agreement in the literature that $V_T/T_I$ is decreased and $f$ is decreased with IRL.(16, 67, 154) However, since $V_T$ appears to be relatively unchanged or insignificantly increased with IRL, changes in ventilation at rest are also variable. Im Hof *et al.* (67) reported an average decrease in ventilation ($\dot{V}_I$) of approximately 10% with an applied IRL but Brack *et al.* (16) did not find any significant changes in $\dot{V}_I$ due to IRL of similar magnitude. Expiratory resistive loading consistently induces a prolongation of expiratory time and an increase in $V_T/T_I$ at rest, just the opposite of IRL. Hill *et al.* (60) reported substantial increases in $V_T$ (24%) with ERL during quiet breathing and both Hill *et al.* (60) and Poon *et al.* (116) found significant decreases in $f$ under such conditions. Expiratory resistive loading appears to reduce ventilation at rest. However, compared to the unloaded condition, reductions are relatively small.(116)

Peak inspiratory (PIF) flow rates under sedentary conditions are significantly reduced with IRL. Decrements in PIF from 10% to as great as 60% have been reported with applied inspiratory resistances.(103, 132, 155) As the level of resistance is increased, the PIF is decreased, the greatest change being produced with relatively small inspiratory loads.(132, 155) Silverman *et al.* (132) reported that the ratio of peak flow to minute volume is highest for individuals during rest with no added inspiratory resistance and lowest for subjects under working conditions with high inspiratory resistance (14.3 $cmH_2O \cdot L^{-1} \cdot s$).

Flook and Kelman (41) exercised eleven male volunteers at 35%, 50%, and 70% of estimated $\dot{V}_{O_2\,max}$, with and without each of three inspiratory resistances (approximately 12.5, 27.5, and 92.5 $cmH_2O \cdot L^{-1} \cdot s$ at 1.42 $L \cdot s^{-1}$) to assess steady-state responses to IRL. There was a progressive decrease in $\dot{V}_E$ at each workload with increasing resistance. Average $\dot{V}_E$ decreased 12% from control with the highest IRL (from roughly 37.3 $L \cdot min^{-1}$ to 29 $L \cdot min^{-1}$) during light work and 38% from control with the 92.5 $cmH_2O \cdot L^{-1} \cdot s$ load (from roughly 55.3 $L \cdot min^{-1}$ to 34.4 $L \cdot min^{-1}$) under moderate steady-state work. During exercise at 70% of estimated $\dot{V}_{O_2\,max}$, average $\dot{V}_E$ decreased 27% from control with the 27.5 $cmH_2O \cdot L^{-1} \cdot s$ resistance (from roughly 75.1 $L \cdot min^{-1}$ to 54.8 $L \cdot min^{-1}$). Data were not reported for the highest IRL under the heaviest work condition because only one volunteer was able to complete the test. Similar decrements in $\dot{V}_E$ at steady-state work rates requiring 80% to 85% of $\dot{V}_{O_2\,max}$ have also been reported using much smaller inspiratory resistive loads (below 8 $cmH_2O \cdot L^{-1} \cdot s$).(19, 47, 73, 87) Applied ERL under steady-state exercise conditions tend to also reduce $\dot{V}_E$ but again, the magnitude of these reductions is much less than those found for IRL.(21, 60, 118, 136)

The changes in $\dot{V}_E$ during non-steady-state maximal efforts mimic those reported during steady-state work for individually applied inspiratory (36, 103, 107) and expiratory resistances.(65) Specifically, there appears to be little difference in $\dot{V}_E$ between unloaded and resistive load conditions under low to moderate rate exercise intensities. However, $\dot{V}_E$ is significantly reduced with resistive loading when maximum performance has been attained.

Breathing against IRL under steady-state working conditions impacts PIF much the same as $\dot{V}E$. Under steady-state exercise of 120 W, Yasukouchi (154) reported a 10% decrement in PIF with inspiratory loads of 2.55 $cmH_2O \cdot L^{-1} \cdot s$ and 3.06 $cmH_2O \cdot L^{-1} \cdot s$ compared to the unloaded condition. When applying IRL near an individual's perceptual threshold of the load, Yasukouchi and Serita (155) also found a 10% decrease in PIF after the load was applied during 100 W of external work. Under similar steady-state conditions, Silverman *et al.* (132) reported roughly the same degree of decline in PIF for comparable IRL. However, as the resistive loads increased above a resistive load of 5.35 $cmH_2O \cdot L^{-1} \cdot s$, these investigators found that PIF decreased 24% to 38% on average compared to the no load condition. Likewise, the maximum PIF value observed at 102 W of external work dropped from 170 $L \cdot min^{-1}$ in the unloaded state to 85 $L \cdot min^{-1}$ with the highest resistive load.

Considering the fact that respirators offer various degrees of resistance to both inhalation and exhalation dependent upon the respirator type and design, a clearer understanding of the impacts of respirator resistance breathing may only be possible by evaluating studies that have used respirators during testing or applied resistances to both inspiration and expiration. With regard to the latter, an argument could be made that all of the IRL and ERL studies discussed to this point applied both inspiratory and expiratory loads because the breathing apparatuses used to collect, direct, and measure ventilation impose some degree of resistance to airflow. In general, such resistances tend to be very low ($< 1$ $cmH_2O \cdot L^{-1} \cdot s$) and may have negligible impacts on ventilation in and of themselves. Thus, for the purposes of this paper, applied IRL and ERL studies will refer only to those investigations that explicitly detail added loads above those inherent to the measuring apparatus.

The work of Silverman *et al.* (131) represents some of the earliest work of applied inspiratory and expiratory breathing resistances. These researchers reported about a 20% decrement in $\dot{V}E$ at the two highest work rates (226 W and 271 W) assessed with a combined breathing resistance of 4.51 $cmH_2O \cdot L^{-1} \cdot s$ during inhalation and 2.89 $cmH_2O \cdot L^{-1} \cdot s$ on exhalation compared to the unloaded condition (0.42 $cmH_2O \cdot L^{-1} \cdot s$ inhalation and 0.21 $cmH_2O \cdot L^{-1} \cdot s$ exhalation resistance) during steady-state cycling exercise. The peak inspiratory and expiratory flows were also reduced by about 15% at the highest work rate and approximately 20% at the 226 W work rate. On average, the highest values of $\dot{V}E$ and PIF reported by Silverman *et al.* (131) during IRL and ERL were 90.3 $L \cdot min^{-1}$ and 240 $L \cdot min^{-1}$.

Deno *et al.* (31) assessed the impacts of equal levels of inspiratory and expiratory resistance on ventilation during progressive exercise to exhaustion as well as during steady-state exercise that was maintained for 60 minutes for each of five resistance conditions. The lowest resistance utilized by these investigators was comparable to the IRL utilized by Silverman *et al.* (131), but roughly double the ERL. Peak $\dot{V}E$ attained at the end of progressive exercise to exhaustion decreased with each increase in breathing resistance. At the lowest resistance level, $\dot{V}E$ was reduced roughly 26% compared to the unloaded condition. The greatest IRL and ERL condition (roughly 40 $cmH_2O \cdot L^{-1} \cdot s$) resulted in a 65% decrease in $\dot{V}E$. During prolonged steady-state exercise, absolute values of $\dot{V}E$ were consistently lower than values measured during short-term testing at the same resistance levels. Average $\dot{V}E$ was reduced roughly 21% compared to the unloaded condition for the lowest resistive load condition, and about 62% for the highest resistance under prolonged exercise designed to exhaust subjects in one hour.

The relative reduction in $\dot{V}_E$ under both exercise scenarios for the resistive load comparable to Silverman *et al.* (131) parallels that reported by these same investigators, indicating that a 20% reduction in $\dot{V}_E$ with resistive loads of approximately 4.5 to 6 $cmH_2O \cdot L^{-1} \cdot s$ is likely.

In summary, information presented for applied resistive loading shows that resistive loading has little impact on $\dot{V}_E$ under resting and low intensity work conditions, but causes significant reductions in $\dot{V}_E$ with increasing work rates above moderate levels. Furthermore, an inverse relationship between breathing resistance and $\dot{V}_E$ is apparent. Resistive load breathing significantly reduces PIF even under resting conditions. Collectively, these findings suggest that peak $\dot{V}_E$ and PIF values reported for unencumbered ventilation are unlikely to be found during resistive load breathing.

## 5.2 Respirator Resistive Loads.

Many studies have described the ventilatory effects of respirators and the topic has been reviewed elsewhere.(106, 120) The changes in ventilation associated with particular respirator types are presented here for laboratory-controlled testing and for the limited data available for both simulated and actual workplace studies. In order to facilitate this review, respirator studies were categorized as tests of air-purifying respirators (non-powered), positive pressure devices, including supplied air and powered air-purifying respirators, or self-contained breathing apparatus respirators.

## 5.3 Air-purifying Respirators.

The use of half-mask air-purifying respirators (APRs) and full-facepiece APRs has been found to result in both higher and lower $\dot{V}_E$ during work of submaximal intensity. During short-duration work (five minutes), Louhevaara *et al.* (92, 94) reported slightly higher $\dot{V}_E$ during the use of a half-mask filtering device compared to unmasked conditions at work rates up to about 60% of $\dot{V}_{O2\,max}$. However, the increased $\dot{V}_E$ was not significant in either case. Harber *et al.* (53) reported non-significant increases in $\dot{V}_E$ with a full-facepiece APR during 6 to 8 minutes of submaximal walking whereas both Jette *et al.* (69) and Hermansen *et al.* (59) found slight, but insignificant, decreases in $\dot{V}_E$ with full-facepiece APRs used during submaximal exercise. Under conditions of longer duration steady-state exercise, White *et al.* (149) reported a significantly higher $\dot{V}_E$ with an APR compared to an unmasked condition after 20 minutes of treadmill walking. However, since this investigation involved full-body encapsulation during heat exposure, the true impact of the APR may be masked by the physiological challenges associated with working in the heat.(69) As for $\dot{V}_E$, APR induced changes in $f$ and $V_T$ were also variable.(53, 59, 75, 149) Louhevaara *et al.* (94) reported a slight decrease in the ventilatory equivalent for oxygen ($\dot{V}_E/\dot{V}_{O2}$) with a half-mask APR during low intensity exercise, a finding supported by observations from Hermansen *et al.*(59) However, the decrease was not significant in either case. Together, these findings indicate that under submaximal work conditions alterations in ventilation are minimal due to APR wear.

Several authors have reported the effects of APRs for moderate to maximal levels of exercise. During both progressive and high-intensity constant load work, ventilation seems to decrease substantially during APR wear compared to unmasked conditions. Jette *et al.* (70) found significant reductions in $\dot{V}_E$ at work intensities above approximately 80% $\dot{V}O_{2\,max}$ and reported $\dot{V}_{E\,max}$ values that were 24% lower than unmasked values during incremental exhaustive load work with a full-facepiece APR. Others found reductions in $\dot{V}_E$ values on the order of about 15% to 43% under high-intensity constant load work conditions with similar respirator conditions.(59, 73) Due to these large decrements in $\dot{V}_E$ but relatively unchanged or slightly reduced rates of oxygen consumption, both Hermansen *et al.* (59) and Jette *et al.* (70) found that APR wear reduced $\dot{V}_E/\dot{V}O_2$ compared to the unmasked conditions at high work rates. Jette *et al.* (70) reported a 9% reduction in $\dot{V}_E/\dot{V}O_2$ with an APR compared to the unmasked condition at maximal work. These finding suggest that APR wear at near maximal and maximal exercise levels cause reduced levels of ventilation compared to unmasked conditions.

## 5.4 Positive-Pressure Respirators.

Literature for respirators included within this category include demand and pressure-demand supplied air respirators (SAR), and powered air-purifying respirators (PAPR), all of which are generally classified as positive-pressure devices. Positive-pressure respirators are intended to maintain pressures within the system's breathing zone slightly above atmospheric pressures during both inhalation and exhalation. Based on the findings from various studies with positive pressure respirators, it appears that the impacts on ventilation with such devices are minimal.

Laboratory experiments performed with demand or pressure-demand supplied air apparatus (full-facepiece) during short-duration submaximal exercise (%$\dot{V}O_{2\,max} < 80\%$) did not show any significant differences in $\dot{V}_E$ responses between masked and unmasked conditions.(94, 119, 121) Harber *et al.* (53) reported similar findings for a powered air-purifying respirator.

During prolonged submaximal, constant load work White *et al.* (149) found no differences in $\dot{V}_E$ between unmasked and pressure-demand apparatus conditions. In contrast, a significantly greater level of ventilation was reported by Wilson *et al.* (152) during the first 60 minutes of constant load walking to exhaustion with a full-facepiece pressure-demand apparatus and at the point of test termination (approximately 56 min). The substantially greater work intensity utilized by these investigators (70% $\dot{V}O_{2\,max}$) compared to White *et al.* (149) (about 24% $\dot{V}O_{2\,max}$) may explain the contrasting results. However, using progressive load maximal efforts to exhaustion, neither Arborelius *et al.* (6) or Dahlbäck and Balldin (29) found significant impacts of positive pressure-demand masks on $\dot{V}_E$.

Data concerning the parameters of PIF and $\dot{V}_E/\dot{V}O_2$ as they relate to supplied air respirators are limited. Louhevaara *et al.* (94) reported a decrease in $\dot{V}_E/\dot{V}O_2$ with a pressure-demand apparatus during submaximal work, particularly at the highest workload that was tested (60% $\dot{V}O_{2\,max}$). However, the decrements in $\dot{V}_E/\dot{V}O_2$ were relatively small when compared to data collected without the respirator. Dahlbäck and Balldin (29) found no significant differences in $\dot{V}_E/\dot{V}O_2$ between positive pressure-demand masks and unmasked conditions during maximal exertion. Wilson *et al.* (152) reported an increased $\dot{V}_E/\dot{V}O_2$ with a pressure-demand apparatus at the end of endurance exercise of 70% $\dot{V}O_{2\,max}$ but the difference did not appear to be significant.

Raven *et al.* (121) found that PIF with a pressure-demand type respirator was lower compared to an unmasked condition during exercise, but not at rest. Furthermore, the degree of reduction in PIF was greater at higher work rates. In a similar investigation with a positive pressure-demand type respirator, these same researchers found no differences in PIF between control and mask wear conditions.(119) Peak inspiratory flows ranged from resting values of 36 $L \cdot min^{-1}$ to 228 $L \cdot min^{-1}$ at about 78% $\dot{V}O_{2\,max}$ in this specific study. Under very hard work conditions (300 W) Dahlbäck and Novak (30) reported PIF rates of approximately 450 $L \cdot min^{-1}$ for one subject while wearing a pressure-demand respirator. Peak inspiratory flow rates of this magnitude are among the highest observed values even for non-respirator conditions. It should be noted that Dahlbäck and Novak (30) explicitly stated that their test subjects were two "well-trained" men, which may account for the high PIF rates according to the previous discussions that indicate that extreme values for both $\dot{V}E$ and PIF tend to be found with highly fit individuals.

Once again, data provided by Wilson *et al.* (152) showed the opposite effect of a pressure-demand apparatus on PIF at the same relative work intensity, albeit for a longer duration. During the first 60 minutes of exercise, average PIF were found to be substantially higher with the SAR apparatus compared to the unmasked condition. Average final PIF were also significantly greater while wearing the respirator (211.4 ± 7.5 $L \cdot min^{-1}$) than without (190.9 ± 7.8 $L \cdot min^{-1}$). Differences in PIF data between Raven *et al.* (119) and Wilson *et al.* (152) may be due to the substantially lower inhalation resistance of the supplied-air apparatus utilized by the latter researchers, which may have permitted greater PIF due to the initially lower efforts required to compensate for the respirator applied resistance. Regardless, it is important to note that the average values for PIF from both studies are comparable.

## 5.5 Self-Contained Breathing Apparatus.

A number of researchers have investigated the ventilatory responses of wearing self-contained breathing apparatus (SCBA) during exercise.(34, 38, 93, 94, 144, 149) During submaximal exercise (≤ 60% $\dot{V}O_{2\,max}$), it appears that with an SCBA, oxygen uptake is greater compared to unmasked conditions, indicating that wearing the air-container of an SCBA (~15 kg) carried as a shoulder harness increases the metabolic burden on the user.(93, 94, 149) Louhevaara *et al.* (94) stated that the load of the SCBA air-container accounted for approximately two-thirds of the increments observed for $\dot{V}O_2$ at the submaximal workloads in their study. Reported changes in $\dot{V}E$ due to SCBA wear during short-duration exercise of equivalent intensities include slight reductions at work below about 50% $\dot{V}O_{2\,max}$ and significant increases at work loads of approximately 60% $\dot{V}O_{2\,max}$ compared to unmasked conditions. (93, 94) The peak levels of $\dot{V}E$ reported by Louhevaara *et al.* (93) averaged 76.7 ± 19.4 $L \cdot min^{-1}$ at the highest workload. Under constant load submaximal work (24% $\dot{V}O_{2\,max}$) of longer duration (≥ 20 min), White *et al.* (149) reported an increase in $\dot{V}E$ due to SCBA wear when compared to control conditions.

In contrast to findings reported for heavy exercise, Verstappen *et al.* (144) reported that no significant differences in $\dot{V}O_2$ and $\dot{V}E$ existed between SCBA wear and control conditions during maximal exercise. A possible explanation for these contrasting results may be that Verstappen *et al.* (144) did not have subjects wearing an SCBA air tank. A remotely placed cylinder with more than the usual volume of air of an SCBA air container provided the air supply to ensure that experimental tests were not terminated due to depletion of tank air. Even though subjects wore a 15 kg lead vest to simulate SCBA air tank weight, other dynamics that could have influenced metabolic responses such as restrictions of a tank harness and postural adjustments used to accomplish tank carrying may not have been adequately simulated by Verstappen *et al.* (144). Nevertheless, the $\dot{V}E$ data reported for SCBA wear at maximal exertion were slightly lower for SCBA conditions compared to control. Without an SCBA, $\dot{V}E_{max}$ averaged 140 ± 15 L·min$^{-1}$ during cycling and 140 ± 22 L·min$^{-1}$ during treadmill exercise. With a positive pressure-demand SCBA, $\dot{V}E_{\mathrm{max}}$ averaged 134 ± 22 L·min$^{-1}$ during cycling and 129 ± 14 L·min$^{-1}$ during treadmill exercise. These represent the highest $\dot{V}E$ values reported in the literature for SCBAs.

Changes in $\dot{V}E/\dot{V}O_2$ reported during SCBA wear include both an increase in values (93, 94) and no differences compared to control conditions.(144) Decrements as high as 20% were reported by Louhevaara *et al.* under heavy work.(93)

In general, the impacts of SCBA usage on ventilation suggest that $\dot{V}E$ are reduced compared to the unencumbered state. This, despite the fact that the added weight associated with carrying the air supply tank of an SCBA increases the metabolic load of the user, a factor that independently increases $\dot{V}E$. Reductions in the $\dot{V}E/\dot{V}O_2$ found with SCBA wear suggest that hypoventilation is likely with such respirator devices, particularly under heavy work conditions.

## 5.6 Workplace Studies with Respirators.

The three main problems associated with measuring the ventilatory effects of respirator usage in the workplace are the technical challenge in measuring ventilation without altering the function of the respirator itself, collecting data without disrupting the user's normal work activities, and the inability to control factors that may impact the physiological parameters of interest.(61) With this in mind, it is not surprising that so few studies of respirator effects in the workplace are found in the open literature.

## 5.7 Air-purifying Respirators in the Workplace.

Louhevaara *et al.* (95) measured heart rate and, when technically possible, $\dot{V}O_2$ and $\dot{V}I$ using an Oxylog, during workshifts in jobs that were completed with filtering devices. During building demolition work with a half-mask APR with dust filters, mean work intensity ranged from 36% to 62% of $\dot{V}O_{2max}$ with $\dot{V}I$ values of 24 L·min$^{-1}$ to 48 L·min$^{-1}$ for the test population. In cast cleaning, welding, and spray painting jobs with both half-mask and full facepiece APRs with combination dust and gas filters, average work intensities were between 12% and 32% of $\dot{V}O_{2max}$ with $\dot{V}I$ values of 16 L·min$^{-1}$ to 33 L·min$^{-1}$.

Using respiratory inductive plethysmography, Hodous *et al.* (61) measured ventilation with and without APR wear on workers performing various job tasks (e.g., working with molten ore, spray painting, sanding and cleaning activities, and sidewalk maintenance). Protective clothing was also worn when required and ambient conditions at all worksites were relatively warm (25°C to 30°C). Respirator wear periods lasted approximately 30 minutes for molten ore work and between five minutes and 40 minutes for spray painting. Based on heart rate data, job-task workloads were considered to be moderate. For all job tasks with an APR, $\dot{V}_E$ averaged $21.5 \pm 7.3$ L·min$^{-1}$.

Kaufman and Hastings (77) recently reported ventilation data recorded on 48 male (mean age $22 \pm 2.1$ years) members of the U.S. Marine Corps while performing simulated tasks relevant to their mission responsibilities. These included simulated decontamination procedures that involved lifting and moving litters and washing down individuals (DECON), a reconnoitering task of walking through various obstacles (RECON), and simulated firefighting tasks. Volunteers wore a full-facepiece APR with a particulate and gas combination filter element for all trials, along with chemical protective clothing. Inspired minute volumes were obtained using a turbine flow meter mounted to the respirator filter element for all trials. Both the DECON and RECON tasks involved relatively low to moderate work over a 60 minutes duration, whereas the simulated firefighting task involved heavy and near maximal exertion during roughly 20 minutes of work. Average ventilation rates for the simulated DECON and RECON tasks were below 40 L·min$^{-1}$. Data analyzed during what the authors identified as a region of peak respiration, which generally corresponded to the heaviest work period during the simulated firefighting task, showed an average $\dot{V}_I$ of $96.4 \pm 18.9$ L·min$^{-1}$. The authors also reported that $\dot{V}_I$ within each subject's region of peak respiration exceeded 100 L·min$^{-1}$ in 42% of the test participants. The single highest recorded $\dot{V}_I$ during the firefighting simulation was 132 L·min$^{-1}$.

Data concerning PIF with APRs were also reported by Kaufman and Hastings (77), who found average PIF below approximately 120 L·min$^{-1}$ during simulated DECON and RECON operations, with average maximal PIF of 220 L·min$^{-1}$ or less. For the simulated firefighting task, PIF averaged $239 \pm 34$ L·min$^{-1}$ and maximum PIF averaged $294 \pm 39$ L·min$^{-1}$. The authors observed a single maximum PIF of 356 L·min$^{-1}$ during firefighting simulation. We have found similar PIF values during testing under heavy exercise conditions with an APR similar to that used by Kaufman and Hastings,(77) albeit with different inhalation resistances.(28)

## 5.8 Positive-Pressure Respirators During Work Activities.

In addition to testing with APRs, Hodous *et al.* (61) measured ventilation with and without SAR wear on workers performing sandblasting and spray painting in an equipment repair facility. The workers performing sandblasting wore a hooded air-line respirator with protective clothing and spray painters wore air-line respirators. Mean heart rates during work with both respirators averaged 114.3 beats·min$^{-1}$ for both job tasks. Louhevaara *et al.* (95) observed comparable heart rates under similar work tasks and respirator conditions and classified such work with supplied-air respirators as light to moderate. According to Hodous *et al.* (61), average ventilation rates under such conditions were $17.7 \pm 5.6$ L·min$^{-1}$. Ventilation data were not reported by Louhevaara *et al.*(95)

Utilizing the same firefighting simulation task as Kaufman and Hastings,(77) Berndtsson and Howie (14) recorded ventilation using a fan-supplied positive pressure breath responsive respirator. In general, the apparatus is a PAPR designed to maintain positive pressure in a full-facepiece respirator with a blower that adjusts the rate of supplied air according to breathing demands of the user. The system is packaged with pressure transducers that monitor pressure changes near the filtering elements and within the oral-nasal cavity of the respirator facepiece. Changes in pressure are used to adjust blower fan speed. The system also permits measurement of total airflow through the respirator's filtering elements and provides a nominal measure of user ventilation. However, there are some unresolved questions that need to be addressed concerning the methods used to determine the pressure-flow curves for measuring ventilation with the system.

In a recent paper, Berndtsson and Ekman (13) describe a technique for measuring ventilation with an APR that appears to be a variant of the principles utilized by a pneumotachograph in that pressure changes across a fixed resistance are related to volumetric flow. There are two potential problems with this method. First, the device, as described by Berndtsson and Ekman,(13) does not use a stable fixed resistance comparable to that of a pneumotachograph, but it uses a P100 particulate filter that would likely have a variable resistance over time due to filter loading. Second, the device does not use a differential pressure transducer that measures pressure on both sides of the resistance element, but rather uses a gage pressure transducer that measures the difference between the applied pressure and atmospheric pressure. If the gage pressure readings are not referenced to absolute pressure, then the pressure readings will be dependent on ambient pressure conditions, which fluctuate due to weather conditions. Thus, a pressure-flow calibration curve developed in a controlled lab may not be applicable when the respirator is worn in another location or at another time with changing weather conditions. It is unclear whether or not Berndtsson and Howie (14) used a similar method for measuring flow rates with the PAPR. Either way, more information on the method used to determine flow rates based on pressure changes within the PAPR system is needed. One final concern is the apparent method used to separate fan-supplied air volumes from ventilation volumes. The method requires the investigator or test administrator to visually inspect the flow tracings and then select the volume of airflow due to the fan from the flow curve that represents the total flow of air through the filters. This purely subjective determination is used in the flow analysis of all subsequent breaths in a given period. No effort is made to validate the selected fan-supplied air volume using an objective method. Thus, interpretation of the flow data reported for the flow measuring system utilized in the fan-supplied positive pressure breath responsive respirator warrants some caution until a better understanding of the device can be obtained. Despite potential shortcomings of their flow-measuring device, the data reported by Berndtsson and Howie (14) are reported here because they are pertinent to the discussion of PAPR use in a simulated work setting.

For the firefighting simulation, Berndtsson and Howie (14) observed an average $\dot{V}I$ of approximately 106 L·min$^{-1}$, with a single maximal $\dot{V}I$ of roughly 175 L·min$^{-1}$ when they assumed about a 17% overflow of fan-supplied air to maintain positive pressure in the respirator facepiece. Mean PIF with the breathe-assist PAPR was reported to be 290 ± 85 L·min$^{-1}$ with maximal values as high as 582 L·min$^{-1}$. However, the authors appear to have failed to account for overflow of the fan-supplied air in the presentation of the PIF rate data. Assuming the same

17% value that was applied for $\dot{V}_I$ data, the average PIF rate becomes 241 L·min$^{-1}$ and the highest observed value would be 483 L·min$^{-1}$.

### 5.9 SCBA Wear During Work Performance.

One respirator wear trial performed in a workplace setting, but under simulated work activities, using an open-circuit SCBA was performed by Smolander *et al.*(134) This investigation required experienced SCBA wearers to perform repair and rescue tasks during a simulated chemical accident at a chemical plant. In brief, subjects worked in pairs to complete a search task that involved climbing a 35 meter high tower, opening and closing vents, sawing and replacing bolts, and carrying a 70 kg litter, all while wearing an SCBA and air tank that weighed 19 kg. Volunteers were also required to wear an impermeable whole-body gas protective suit (additional weight of 8 kg). The mean $\dot{V}_E$ for the work period was estimated from the decrements in SCBA air tank pressures. The total work time averaged 37 ± 2 minutes, but only one volunteer completed all work tasks whereas the remaining subjects terminated testing because their air tanks were emptied. A rough estimate of the work intensity associated with the work tasks was 70% of $\dot{V}O_{2\,max}$. Minute volumes ranged from 42 L·min$^{-1}$ to 70 L·min$^{-1}$ and averaged 56 ± 3 L·min$^{-1}$ for all subjects.

Lusa *et al.* (98) assessed the physiological responses of firefighting students during simulated smoke diving with an SCBA in the heat. The simulated smoke-diving task was completed in a building designed to simulate fires aboard a ship, including smoke and heat. Subjects worked in pairs at their own pace to search out and save a victim (70 kg litter). During the task, subjects wore an open-circuit SCBA with a full-facemask and nosecup and fire-protective clothing (total equipment weight of 25 kg). The smoke-diving task was performed with an average simulator temperature of 110 ± 12°C and took between 13 and 17 minutes for all subjects to complete. The estimated level of oxygen consumption during smoke diving was 2.4 ± 0.5 L·min$^{-1}$ for all subjects, corresponding to roughly 60 ± 12% of $\dot{V}O_{2\,max}$. Minute volumes, estimated according to the decrease in the air tank pressures, ranged from 40 L·min$^{-1}$ to 97 L min$^{-1}$ and averaged 54 ± 10 L·min$^{-1}$.

Both the Smolander *et al.* (134) and Lusa *et al.* (98) studies simulated heavy physical work activities that would be completed during SCBA and protective clothing wear. Louhevaara *et al.* (95) estimated work rates between 54% and 75% $\dot{V}O_{2\,max}$ and minute volumes of 45 L·min$^{-1}$ to 70 L·min$^{-1}$ for the same work simulations with SCBAs. The values for work intensity are very similar to results derived by Sothmann *et al.* (135) who measured heart rate responses of firefighters during actual structural firefighting and used the heart rate to $\dot{V}O_2$ relationship to estimate a work intensity of 63 ± 14% of $\dot{V}O_{2\,max}$. Likewise, the values of $\dot{V}_E$ are comparable to previously discussed data obtained during SCBA wear under similar levels of aerobic strain.(94, 95) Collectively, these findings suggest that average ventilation rates between 50 L·min$^{-1}$ and 60 L·min$^{-1}$ are commonplace during SCBA wear in the workplace when heavy physical work is being performed. Data from both the simulated workplace and laboratory studies that tested unmodified SCBAs suggest that peak levels of $\dot{V}_E$ will rarely exceed 100 L·min$^{-1}$.

## 6. CONCLUSIONS AND RECOMMENDATIONS

It is apparent from the review of the literature presented herein that specific values for human ventilation during occupational tasks in work environments are limited. Since measurements of ventilation rates are available for a minimal number of physical activities, this review included estimates of $\dot{V}_E$ based on energy expenditure rates reported for a wide range of occupational activities. In most instances, estimates of $\dot{V}_E$ were calculated based on the exponential relationships between $\dot{V}_E$ and $\dot{V}O_2$ reported by Hagan and Smith (51) and Baba *et al.*,(10) thus providing a range of predicted $\dot{V}_E$ values for a given energy expenditure. Since human ventilatory responses can vary dramatically based on cardiovascular fitness, body dimensions, gender, and age, not to mention the work environment (e.g., temperature and humidity) and the intensity and biomechanical dynamics of activity, it was reasoned that a range of $\dot{V}_E$ values would better define anticipated occupational ventilation rates.

A summary analysis of both measured and estimated $\dot{V}_E$ indicated a range of $\dot{V}_E$ from about 8 L·min$^{-1}$ to 162 L·min$^{-1}$ for work activities that spanned mild to exhaustive workloads. The mean $\dot{V}_E$ for all data was 38.5 ± 16.6 L·min$^{-1}$ and the 95th percentile for $\dot{V}_E$ was 73.3 L·min$^{-1}$. Interestingly, the mean $\dot{V}_E$ of 38.5 ± 16.6 L·min$^{-1}$ is very similar to the 40 L·min$^{-1}$ cyclic flow rate currently employed in chemical agent respirator system testing required by NIOSH for certification of SCBA and APR respirators to CBRN standards. However, based on the 95th percentile for $\dot{V}_E$ observed in this review, it appears that higher cyclic flow rates may be needed to account for a greater percentage of ventilation rates that are likely to occur in the workplace. When compared to minute volumes observed during incremental exercise testing to exhaustion, testing that is designed to determine maximum physiological responses, the distribution of estimated $\dot{V}_E$ values for occupational work tasks indicated that minute volumes rarely reach $\dot{V}_{E\,max}$ values such as those reported by Blackie *et al.*(15) Therefore, it appears that a minute volume of about 73 L·min$^{-1}$ sufficiently represents the upper end of workplace ventilation rates. Higher $\dot{V}_E$ values are likely to be found in the workplace, however all indications are that these occurrences will not be the norm. An increase in cyclic flow rates used in CBRN certification testing should be considered to better represent ventilation rates found in the workplace. If the desire is to encompass a higher percentage of possible human ventilation rates independent of the workplace, then the recommendation would be to utilize a $\dot{V}_E$ of 114 L·min$^{-1}$, the average $\dot{V}_{E\,max}$ values reported by Blackie *et al.* (15) for 20 to 29 year old males.

The data in the foregoing review that reported PIF rates for unencumbered ventilation from work intensities ranging from rest to exhaustive exercise, as well as during speech, showed that PIF rates generally increase exponentially with increasing work rate. High estimates of PIF based on the mean and 95th percentile $\dot{V}_E$ values found in the analysis of workplace ventilation rates were 183 L·min$^{-1}$ and 295 L·min$^{-1}$, respectively. These PIF rates correspond with average PIF data found in the literature and suggest that a PIF of approximately 300 L·min$^{-1}$ would adequately represent 95% of the peaks occurring during occupational task performance. However, since PIF in excess of 300 L·min$^{-1}$ has been measured during high intensity work (326 L·min$^{-1}$ and 485 L·min$^{-1}$ (Coyne, personal communication, February 27, 2004)), an argument for setting PIF rate test standards above 300 L·min$^{-1}$ is difficult to dismiss. The question becomes what is a reasonable limit for PIF? One plausible solution is to estimate the upper limit of a PIF rate range based on maximal $\dot{V}_E$ data measured, not estimated, during maximal load work. Again, we refer to the average $\dot{V}_{E\,max}$ of 114 ± 23 L·min$^{-1}$ reported by Blackie *et al.*(15) The PIF rate prediction interval derived from this $\dot{V}_E$ is about 329 L·min$^{-1}$ to 428 L·min$^{-1}$. If one standard deviation is added to the average $\dot{V}_{E\,max}$ as a safety factor or to account for potential shortfalls with prediction intervals, $\dot{V}_E$ increases to 137 L·min$^{-1}$ and the PIF prediction interval changes to 380 L·min$^{-1}$ to 503 L·min$^{-1}$. These findings indicate that the upper limits of PIF rate are likely to fall somewhere between roughly 430 and 500 L·min$^{-1}$ and suggest that PIF rates of this magnitude should adequately represent peak values for most physical activities. Bearing in mind that peak inspiratory flows of 500 L·min$^{-1}$ are likely to be found only during very short-duration, exhaustive work loads, the occurrence of such extreme flows should be considered extremely rare during normal workplace activities. In addition, since a PIF of 430 L·min$^{-1}$ is 1.4 times greater than the highest PIF estimates based on the 95th percentile workplace ventilation rate (i.e., about 300 L·min$^{-1}$), it is recommended that utilizing a PIF rate of this magnitude would be adequate for filter and respirator testing. Finally, since peak inspiratory flows are representative of the single highest rate of flow during a given inhalation phase, caution must be exercised in how the impacts of PIF on respirator or filter performance should be assessed. Ideally, testing should mimic real world use as much as possible. Our recommendation would be to test PIF impacts under cyclic flow conditions as would be observed during human breathing to gain a truer understanding of respirator or filter performance under extreme flow conditions. Application of a constant rate airflow that equals a chosen PIF upper limit would not be representative of real use conditions for most, if not all, respirator types.

According to the literature concerning ventilatory responses to work during respirator wear reviewed herein, it appears that high $\dot{V}_E$ and PIF rates are attainable while wearing most respirator types during heavy work. However, peak values of $\dot{V}_E$ and PIF will generally be lower than those achieved for unmasked test activities, particularly during heavy work with APR and SCBA respirators. Supplied-air systems appear to have less of an impact on ventilation by comparison. Despite the apparent damping impacts of APR and SCBA systems on peak ventilation values, the current recommendation is to utilize data for the unencumbered state for test flow rates and not to attempt to establish multiple flow rate criterion based on respirator types.

Finally, this review reemphasized the gap in data pertaining to human breathing responses to real-world daily activities. Despite the potential shortcomings of the methods adopted herein for estimating $\dot{V}_E$ and PIF rates, we believe that this review serves as a first step toward defining ventilatory responses in the workplace. Until further research that utilizes a reliable, repeatable, and virtually unnoticeable method for measuring human ventilation can be implemented, a truer understanding cannot be achieved.

## 7. FUTURE CONSIDERATIONS

As an adjunct effort to this literature review, work has been initiated to gather, compile, and analyze human ventilation data from various sources. The objective of this work is to obtain raw data from willing investigators who have recently measured and recorded breathing volumes and other respiratory data during respirator wear test trials. Once gathered, the data will be categorized according to parameters such as respirator type and external workload conditions and reanalyzed. The purpose of the analysis is to validate the current knowledge base on ventilatory responses to respirator wear. In addition, the data will be scrutinized to identify knowledge gaps, which may be useful for setting future investigations of respirator wear. Ventilation data provided to date is under review and an initial database of independent and dependent variables has been designed and partially populated. Data analysis will be initiated once the database has been finalized.

Other work items that should be considered as paramount to developing a comprehensive understanding of workplace breathing rates for respirator users include the following:

1. Determination of the relationship between $\dot{V}_E$ and $\dot{V}_{O_2}$ for a representative population of respirator users. The exponential functions reported by Hagan and Smith (51) and Baba *et al.* (10) utilized to derive $\dot{V}_E$ from $\dot{V}_{O_2}$ in this literature review have provided useful estimates of ventilation for various work tasks. However, additional research that establishes a relationship between $\dot{V}_E$ and $\dot{V}_{O_2}$ based on actual respirator users should be considered so that estimates of $\dot{V}_E$ based on energy expenditure better reflect this worker demographic.

2. Development of a flow-measuring device for quantifying breathing patterns of respirator users at work. As evident from the literature review, data that quantify ventilation rates of workers performing everyday tasks is sparse. Measuring the ventilatory effects of respirator usage in the workplace involves the technical challenges of measuring ventilation without altering the function of the respirator and collecting data without disrupting the user's normal work activities. In order to gain a better understanding of worker breathing parameters, an effort that develops a flow measuring device capable of measuring breathing patterns without increasing respirator encumbrance or interfering with protective capabilities during respirator wear is warranted. Without such a device, respirator test standards for airflows that are supposed to reflect actual user ventilation will continue to be based on airflow parameters measured in laboratory settings or estimated from physical activity workloads.

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# APPENDIX

## ESTIMATES OF VENTILATION BASED ON OCCUPATIONAL METABOLIC RATES FROM ISO 8996 AND THE COMPENDIUM OF PHYSICAL ACTIVITIES

**Table A.1. Estimates of Minute Ventilation for Males of Various Occupations**

| *Occupation* | *Metabolic rate (W·m$^{-2}$)* | $\dot{V}_{O_2}$ *(L·min$^{-1}$)* | *Estimated* $\dot{V}_E$ *(L·min$^{-1}$)*[*] |
|---|---|---|---|
| **Craftsmen** | | | |
| Bricklayer | 110 to 160 | 0.57 to 0.83 | 23.4 to 29.0 |
| Carpenter | 110 to 175 | 0.57 to 0.90 | 23.4 to 31.0 |
| Glazier | 90 to 125 | 0.46 to 0.64 | 21.4 to 24.9 |
| Painter | 100 to 130 | 0.52 to 0.67 | 22.4 to 25.5 |
| Baker | 110 to 140 | 0.57 to 0.72 | 23.4 to 26.6 |
| Butcher | 105 to 140 | 0.54 to 0.72 | 22.9 to 26.6 |
| Clock/watch repairer | 55 to 70 | 0.28 to 0.36 | 18.4 to 19.6 |
| **Mining Industry** | | | |
| Haulage operator | 70 to 85 | 0.36 to 0.44 | 19.6 to 21.0 |
| Coal hewer | 140 to 240 | 0.72 to 1.24 | 26.6 to 41.1 |
| Coke oven man | 115 to 175 | 0.59 to 0.90 | 23.9 to 31.0 |
| **Iron & Steel Industry** | | | |
| Blast Furnace Man | 170 to 220 | 0.88 to 1.14 | 30.3 to 37.7 |
| Electric Furnace Man | 125 to 145 | 0.64 to 0.75 | 24.9 to 27.2 |
| Hand moulder | 140 to 240 | 0.72 to 1.24 | 26.6 to 41.1 |
| Machine moulder | 105 to 165 | 0.54 to 0.85 | 22.9 to 29.7 |
| Foundryman | 140 to 240 | 0.72 to 1.24 | 26.6 to 41.1 |
| **Iron/Metal working** | | | |
| Smith | 90 to 200 | 0.46 to 1.03 | 21.4 to 34.5 |
| Welder | 75 to 125 | 0.39 to 0.64 | 20.1 to 24.9 |
| Turner | 75 to 125 | 0.39 to 0.64 | 20.1 to 24.9 |
| Drilling machine operator | 80 to 140 | 0.41 to 0.72 | 20.5 to 26.6 |
| Precision mechanic | 70 to 110 | 0.36 to 0.57 | 19.6 to 23.4 |
| **Graphic Profession** | | | |
| Hand compositor | 70 to 95 | 0.36 to 0.49 | 19.6 to 21.9 |
| Book binder | 75 to 100 | 0.39 to 0.52 | 20.1 to 22.4 |
| **Agriculture** | | | |
| Gardener | 115 to 190 | 0.59 to 0.98 | 23.9 to 33.1 |
| Tractor Driver | 85 to 110 | 0.44 to 0.57 | 21.0 to 23.4 |
| **Traffic** | | | |
| Cab driver | 70 to 90 | 0.36 to 0.46 | 19.6 to 21.4 |
| Bus driver | 75 to 125 | 0.39 to 0.64 | 20.1 to 24.9 |
| Tramway driver | 80 to 115 | 0.41 to 0.59 | 20.5 to 23.9 |
| Electric trolley driver | 80 to 125 | 0.41 to 0.64 | 20.5 to 24.9 |
| Crane driver | 65 to 145 | 0.34 to 0.75 | 19.2 to 27.2 |
| **Various Professions** | | | |
| Laboratory assistant | 85 to 100 | 0.44 to 0.52 | 21.0 to 22.4 |
| Teacher | 85 to 100 | 0.44 to 0.52 | 21.0 to 22.4 |
| Shop girl | 100 to 120 | 0.52 to 0.62 | 22.4 to 24.4 |
| Secretary | 70 to 85 | 0.36 to 0.44 | 19.6 to 21.0 |

[*] Based on the exponential function of Baba *et al.*(10) only.

**Table A.2. Estimates of Minute Ventilation for Females of Various Occupations**

| *Occupation* | *Metabolic rate (W·m$^{-2}$)* | $\dot{V}_{O_2}$ *(L·min$^{-1}$)* | *Estimated* $\dot{V}_E$ *(L·min$^{-1}$)** |
|---|---|---|---|
| **Craftsmen** | | | |
| Bricklayer | 110 to 160 | 0.50 to 0.73 | 22.2 to 26.9 |
| Carpenter | 110 to 175 | 0.50 to 0.80 | 22.2 to 28.5 |
| Glazier | 90 to 125 | 0.41 to 0.57 | 20.5 to 23.5 |
| Painter | 100 to 130 | 0.46 to 0.60 | 21.3 to 23.9 |
| Baker | 110 to 140 | 0.50 to 0.64 | 22.2 to 24.9 |
| Butcher | 105 to 140 | 0.48 to 0.64 | 21.7 to 24.9 |
| Clock/watch repairer | 55 to 70 | 0.25 to 0.32 | 17.9 to 19.0 |
| **Mining Industry** | | | |
| Haulage operator | 70 to 85 | 0.32 to 0.39 | 19.0 to 20.1 |
| Coal hewer | 140 to 240 | 0.64 to 1.10 | 24.9 to 36.6 |
| Coke oven man | 115 to 175 | 0.53 to 0.80 | 22.6 to 28.5 |
| **Iron & Steel Industry** | | | |
| Blast furnace person | 170 to 220 | 0.78 to 1.01 | 27.9 to 33.9 |
| Electric furnace person | 125 to 145 | 0.57 to 0.66 | 23.5 to 25.4 |
| Hand moulder | 140 to 240 | 0.64 to 1.10 | 24.9 to 36.6 |
| Machine moulder | 105 to 165 | 0.48 to 0.76 | 21.7 to 27.4 |
| Foundryman | 140 to 240 | 0.64 to 1.10 | 24.9 to 36.6 |
| **Iron/Metal working** | | | |
| Smith | 90 to 200 | 0.41 to 0.92 | 20.5 to 31.4 |
| Welder | 75 to 125 | 0.34 to 0.57 | 19.4 to 23.5 |
| Turner | 75 to 125 | 0.34 to 0.57 | 19.4 to 23.5 |
| Drilling machine operator | 80 to 140 | 0.37 to 0.64 | 19.7 to 24.9 |
| Precision mechanic | 70 to 110 | 0.32 to 0.50 | 19.0 to 22.2 |
| **Graphic Profession** | | | |
| Hand compositor | 70 to 95 | 0.32 to 0.44 | 19.0 to 20.9 |
| Book binder | 75 to 100 | 0.34 to 0.46 | 19.4 to 21.3 |
| **Agriculture** | | | |
| Gardener | 115 to 190 | 0.53 to 0.87 | 22.6 to 30.2 |
| Tractor Driver | 85 to 110 | 0.39 to 0.50 | 20.1 to 22.2 |
| **Traffic** | | | |
| Cab driver | 70 to 90 | 0.32 to 0.41 | 19.0 to 20.5 |
| Bus driver | 75 to 125 | 0.34 to 0.57 | 19.4 to 23.5 |
| Tramway driver | 80 to 115 | 0.37 to 0.53 | 19.7 to 22.6 |
| Electric trolley driver | 80 to 125 | 0.37 to 0.57 | 19.7 to 23.5 |
| Crane driver | 65 to 145 | 0.30 to 0.66 | 18.6 to 25.4 |
| **Various Professions** | | | |
| Laboratory assistant | 85 to 100 | 0.39 to 0.46 | 20.1 to 21.3 |
| Teacher | 85 to 100 | 0.39 to 0.46 | 20.1 to 21.3 |
| Shop girl | 100 to 120 | 0.46 to 0.55 | 21.3 to 23.0 |
| Secretary | 70 to 85 | 0.32 to 0.39 | 19.0 to 20.1 |

*Based on the exponential function of Baba *et al.*(10) only.

**Table A.3. Metabolic Rates for Typical Work Activities Listed in ISO Standard 8996 and Estimates of Ventilation for Males and Females**

| | | *Males* | | | *Females* | | |
|---|---|---|---|---|---|---|---|
| | | | *Estimated* $\dot{V}_E$ *($L\cdot min^{-1}$)* | | | *Estimated* $\dot{V}_E$ *($L\cdot min^{-1}$)* | |
| *Activity* | *Metabolic rate ($W\cdot m^{-2}$)* | $\dot{V}O_2$ *($L\cdot min^{-1}$)* | *Hagan and Smith* | *Baba et al.* | $\dot{V}O_2$ *($L\cdot min^{-1}$)* | *Hagan and Smith* | *Baba et al.* |
| **Building industry** | | | | | | | |
| ***Brick laying (building wall of same area)*** | | | | | | | |
| solid brick (weight 3,8 kg) | 150 | 0.77 | | 27.8 | 0.69 | | 25.9 |
| hollow brick (weight 4,2 kg) | 140 | 0.72 | | 26.6 | 0.64 | | 24.9 |
| hollow brick (weight 15,3 kg) | 125 | 0.64 | | 24.9 | 0.57 | | 23.5 |
| hollow brick (weight 23,4 kg) | 135 | 0.70 | | 26.0 | 0.62 | | 24.4 |
| ***Fabrication of finished concrete*** | | | | | | | |
| Part forming and stripping the mould | 180 | 0.93 | 26.2 | 31.7 | 0.83 | | 29.0 |
| Putting in steel stretchers | 130 | 0.67 | | 25.5 | 0.60 | | 23.9 |
| Pouring in concrete | 180 | 0.93 | 26.2 | 31.7 | 0.83 | | 29.0 |
| ***Building a dwelling*** | | | | | | | |
| Mixing cement | 155 | 0.80 | | 28.4 | 0.71 | | 26.4 |
| Pouring concrete for foundation | 275 | 1.42 | 33.8 | 47.9 | 1.26 | 31.1 | 41.9 |
| Compacting concrete by vibrations | 220 | 1.14 | 29.2 | 37.7 | 1.01 | 27.4 | 33.9 |
| Forming mould | 180 | 0.93 | 26.2 | 31.7 | 0.83 | | 29.0 |
| Loading wheelbarrow w/stones & mortar | 275 | 1.42 | 33.8 | 47.9 | 1.26 | 31.1 | 41.9 |
| **Iron and steel industry** | | | | | | | |
| ***Blast furnace*** | | | | | | | |
| Preparing runners for tapping | 340 | 1.75 | 40.2 | 63.5 | 1.56 | 36.3 | 53.8 |
| Tapping | 430 | 2.22 | 51.0 | | 1.97 | 44.9 | 76.2 |
| ***Moulding (hand moulding)*** | | | | | | | |
| Moulding medium sized pieces | 285 | 1.47 | 34.7 | 50.0 | 1.31 | 31.9 | 43.5 |
| Ramming with pneumatic hammer | 175 | 0.90 | 25.9 | 31.0 | 0.80 | | 28.5 |
| Moulding small pieces | 140 | 0.72 | | 26.6 | 0.64 | | 24.9 |
| ***Machine moulding*** | | | | | | | |
| Pouring off castings | 125 | 0.64 | | 24.9 | 0.57 | | 23.5 |
| Casting, one-man ladle | 220 | 1.14 | 29.2 | 37.7 | 1.01 | 27.4 | 33.9 |

**Table A.3. Metabolic Rates for Typical Work Activities Listed in ISO Standard 8996 and Estimates of Ventilation for Males and Females (Continued)**

| *Activity* | *Metabolic rate ($W \cdot m^{-2}$)* | *Males* | | | *Females* | | |
|---|---|---|---|---|---|---|---|
| | | $\dot{V}_{O_2}$ *($L \cdot min^{-1}$)* | *Estimated $\dot{V}_E$ ($L \cdot min^{-1}$)* | | $\dot{V}_{O_2}$ *($L \cdot min^{-1}$)* | *Estimated $\dot{V}_E$ ($L \cdot min^{-1}$)* | |
| | | | *Hagan and Smith* | *Baba et al.* | | *Hagan and Smith* | *Baba et al.* |
| Casting, two-man ladle | 210 | 1.08 | 28.4 | 36.1 | 0.96 | 26.7 | 32.6 |
| Casting from ladle hanging on crane | 190 | 0.98 | 27.0 | 33.1 | 0.87 | | 30.2 |
| **Fettling Shop** | | | | | | | |
| Working with pneumatic hammer | 175 | 0.90 | 25.9 | 31.0 | 0.80 | | 28.5 |
| Grinding, cutting | 175 | 0.90 | 25.9 | 31.0 | 0.80 | | 28.5 |
| **Forestry** | | | | | | | |
| ***Transporting & working with an axe*** | | | | | | | |
| Walking & transporting (7 kg) in forest, 4 km/h | 285 | 1.47 | 34.7 | 50.0 | 1.31 | 31.9 | 43.5 |
| Carrying power saw (18 kg) in hands, 4 km/h | 385 | 1.99 | 45.3 | 77.2 | 1.77 | 40.4 | 64.1 |
| Working with axe (2 kg) 33 blows/min | 500 | 2.58 | 61.4 | | 2.29 | 53.0 | |
| Cutting root stolons with axe | 375 | 1.93 | 44.1 | 73.9 | 1.72 | 39.4 | 61.6 |
| Chopping off branches | 415 | 2.14 | 49.0 | 87.9 | 1.90 | 43.3 | 71.9 |
| **Sawing** | | | | | | | |
| Cutting across grain, 2-man crosscut saw | | | | | | | |
| 60 double pulls/min, 20 $cm^2$ per double pull | 415 | 2.14 | 49.0 | 87.9 | 1.90 | 43.3 | 71.9 |
| 40 double pulls/min, 20 $cm^2$ per double pull | 240 | 1.24 | 30.8 | 41.1 | 1.10 | 28.7 | 36.6 |
| Felling with power saw | | | | | | | |
| One-man power saw | 235 | 1.21 | 30.4 | 40.2 | 1.08 | 28.3 | 35.9 |
| Two-man power saw | 205 | 1.06 | 28.1 | 35.3 | 0.94 | 26.4 | 32.0 |
| Cutting across the grain | | | | | | | |
| One-man power saw | 205 | 1.06 | 28.1 | 35.3 | 0.94 | 26.4 | 32.0 |
| Two-man power saw | 190 | 0.98 | 27.0 | 33.1 | 0.87 | | 30.2 |

**Table A.3. Metabolic Rates for Typical Work Activities Listed in ISO Standard 8996 and Estimates of Ventilation for Males and Females (Continued)**

| | | *Males* | | | *Females* | | |
|---|---|---|---|---|---|---|---|
| | | | *Estimated* $\dot{V}_E$ *(L·min$^{-1}$)* | | | *Estimated* $\dot{V}_E$ *(L·min$^{-1}$)* | |
| *Activity* | *Metabolic rate (W·m$^{-2}$)* | $\dot{V}O_2$ *(L·min$^{-1}$)* | *Hagan and Smith* | *Baba et al.* | $\dot{V}O_2$ *(L·min$^{-1}$)* | *Hagan and Smith* | *Baba et al.* |
| **Agriculture** | | | | | | | |
| Digging with spade (24 lifts/min) | 380 | 1.96 | 44.7 | 75.5 | 1.74 | 39.9 | 62.8 |
| Ploughing with team of horses | 235 | 1.21 | 30.4 | 40.2 | 1.08 | 28.3 | 35.9 |
| Ploughing with a tractor | 170 | 0.88 | | 30.3 | 0.78 | | 27.9 |
| Fertilizing farmland | | | | | | | |
| Hand sowing | 280 | 1.44 | 34.2 | 48.9 | 1.28 | 31.5 | 42.7 |
| Sowing with manure spreader drawn by horses | 250 | 1.29 | 31.6 | 42.9 | 1.15 | 29.4 | 38.0 |
| Sowing with a tractor | 95 | 0.49 | | 21.9 | 0.44 | | 20.9 |
| Hoeing turnips (weight of hoe 1.25 kg) | 170 | 0.88 | | 30.3 | 0.78 | | 27.9 |

## Table A.4. MET Intensities and Estimates of Ventilation for Occupational Activities Listed in the Compendium of Physical Activities (2000)

| | | | *Males* | | | *Females* | | |
|---|---|---|---|---|---|---|---|---|
| | | | | $\dot{V}_E$ *(L·min$^{-1}$)* | | | $\dot{V}_E$ *(L·min$^{-1}$)* | |
| *Code* | *Description* | *METs* | $\dot{V}O_2$ $^A$ *(L·min$^{-1}$)* | *Hagan & Smith* | *Baba* | $\dot{V}O_2$ $^B$ *(L·min$^{-1}$)* | *Hagan & Smith* | *Baba* |
| 11010 | Bakery, general, moderate effort | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11015 | Bakery, light effort | 2.5 | 0.66 | | 25.2 | 0.53 | | 22.5 |
| 11020 | Bookbinding | 2.3 | 0.60 | | 24.1 | 0.48 | | 21.8 |
| 11030 | Building road (including hauling debris, driving heavy machinery) | 6.0 | 1.58 | 36.6 | 54.6 | 1.26 | 31.1 | 41.9 |
| 11035 | Building road, directing traffic (standing) | 2.0 | 0.53 | | 22.5 | 0.42 | | 20.6 |
| 11040 | Carpentry, general | 3.5 | 0.92 | 26.1 | 31.4 | 0.74 | | 26.9 |
| 11050 | Carrying heavy loads, such as bricks | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11060 | Caring moderate loads up stairs, moving boxes (16-40 pounds) | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11070 | Chambermaid, making bed (nursing) | 2.5 | 0.66 | | 25.2 | 0.53 | | 22.5 |
| 11080 | Coal mining, drilling coal, rock | 6.5 | 1.71 | 39.2 | 61.0 | 1.37 | 32.9 | 45.7 |
| 11090 | Coal mining, erecting supports | 6.5 | 1.71 | 39.2 | 61.0 | 1.37 | 32.9 | 45.7 |
| 11100 | Coal mining, general | 6.0 | 1.58 | 36.6 | 54.6 | 1.26 | 31.1 | 41.9 |
| 11110 | Coal mining, shoveling coal | 7.0 | 1.84 | 41.9 | 68.1 | 1.47 | 34.7 | 50.0 |
| 11120 | Construction, outside, remodeling | 5.5 | 1.44 | 34.2 | 48.9 | 1.16 | 29.5 | 38.3 |
| 11121 | Custodial work - buffing the floor with electric buffer | 3.0 | 0.79 | | 28.1 | 0.63 | | 24.6 |
| 11122 | Custodial work - cleaning sink and toilet, light effort | 2.6 | 0.68 | | 25.6 | 0.54 | | 22.9 |
| 11123 | Custodial work - dusting, light effort | 2.6 | 0.68 | | 25.6 | 0.54 | | 22.9 |
| 11124 | Custodial work - feathering arena floor, moderate effort | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11125 | Custodial work - general cleaning, moderate effort | 3.5 | 0.92 | 26.1 | 31.4 | 0.74 | | 26.9 |
| 11126 | Custodial work - mopping, moderate effort | 3.5 | 0.92 | 26.1 | 31.4 | 0.74 | | 26.9 |
| 11127 | Custodial work - take out trash, moderate effort | 3.0 | 0.79 | | 28.1 | 0.63 | | 24.6 |
| 11128 | Custodial work - vacuuming, light effort | 2.5 | 0.66 | | 25.2 | 0.53 | | 22.5 |
| 11129 | Custodial work - vacuuming, moderate effort | 3.0 | 0.79 | | 28.1 | 0.63 | | 24.6 |
| 11130 | Electrical work, plumbing | 3.5 | 0.92 | 26.1 | 31.4 | 0.74 | | 26.9 |
| 11140 | Farming, baling hay, cleaning barn, poultry work, vigorous effort | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11150 | Farming, chasing cattle, non-strenuous (walking), moderate effort | 3.5 | 0.92 | 26.1 | 31.4 | 0.74 | | 26.9 |
| 11151 | Farming, chasing cattle or other livestock on horseback, moderate effort | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11152 | Farming, chasing cattle or other livestock, driving, light effort | 2.0 | 0.53 | | 22.5 | 0.42 | | 20.6 |
| 11160 | Farming, driving harvester, cutting hay, irrigation work | 2.5 | 0.66 | | 25.2 | 0.53 | | 22.5 |

## Table A.4. MET Intensities and Estimates of Ventilation for Occupational Activities Listed in the Compendium of Physical Activities (2000) (Continued)

| | | | *Males* | | | *Females* | | |
|---|---|---|---|---|---|---|---|---|
| | | | | $\dot{V}_E$ *(L·min$^{-1}$)* | | | $\dot{V}_E$ *(L·min$^{-1}$)* | |
| *Code* | *Description* | *METs* | $\dot{V}O_2{}^{A}$ *(L·min$^{-1}$)* | *Hagan & Smith* | *Baba* | $\dot{V}O_2{}^{B}$ *(L·min$^{-1}$)* | *Hagan & Smith* | *Baba* |
| 11170 | Farming, driving tractor | 2.5 | 0.66 | | 25.2 | 0.53 | | 22.5 |
| 11180 | Farming, feeding small animals | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11190 | Farming, feeding cattle, horses | 4.5 | 1.18 | 29.9 | 39.2 | 0.95 | 26.5 | 32.1 |
| 11191 | Farming, hauling water for animals, general hauling water | 4.5 | 1.18 | 29.9 | 39.2 | 0.95 | 26.5 | 32.1 |
| 11192 | Farming, taking care of animals (grooming, brushing, shearing sheep, assisting with birthing, medical care, branding) | 6.0 | 1.58 | 36.6 | 54.6 | 1.26 | 31.1 | 41.9 |
| 11200 | Farming, forking straw bales, cleaning corral or barn, vigorous effort | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11210 | Farming, milking by hand, moderate effort | 3.0 | 0.79 | | 28.1 | 0.63 | | 24.6 |
| 11220 | Farming, milking by machine, light effort | 1.5 | 0.39 | | 20.2 | 0.32 | | 18.9 |
| 11230 | Farming, shoveling grain, moderate effort | 5.5 | 1.44 | 34.2 | 48.9 | 1.16 | 29.5 | 38.3 |
| 11240 | Fire fighter, general | 12.0 | 3.15 | 82.4 | | 2.52 | 59.6 | |
| 11245 | Fire fighter, climbing ladder with full gear | 11.0 | 2.89 | 72.0 | | 2.31 | 53.5 | |
| 11246 | Fire fighter, hauling hoses on ground | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11250 | Forestry, ax chopping, fast | 17.0 | 4.46 | 162.0 | | 3.57 | 102.3 | |
| 11260 | Forestry, ax chopping, slow | 5.0 | 1.31 | 32.0 | 43.8 | 1.05 | 27.9 | 35.1 |
| 11270 | Forestry, barking trees | 7.0 | 1.84 | 41.9 | 68.1 | 1.47 | 34.7 | 50.0 |
| 11280 | Forestry, carrying logs | 11.0 | 2.89 | 72.0 | | 2.31 | 53.5 | |
| 11290 | Forestry, felling trees | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11300 | Forestry, general | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11310 | Forestry, hoeing | 5.0 | 1.31 | 32.0 | 43.8 | 1.05 | 27.9 | 35.1 |
| 11320 | Forestry, planting by hand | 6.0 | 1.58 | 36.6 | 54.6 | 1.26 | 31.1 | 41.9 |
| 11330 | Forestry, sawing by hand | 7.0 | 1.84 | 41.9 | 68.1 | 1.47 | 34.7 | 50.0 |
| 11340 | Forestry, sawing, power | 4.5 | 1.18 | 29.9 | 39.2 | 0.95 | 26.5 | 32.1 |
| 11350 | Forestry, trimming trees | 9.0 | 2.36 | 54.9 | | 1.89 | 43.1 | 71.2 |
| 11360 | Forestry, weeding | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11370 | Furriery | 4.5 | 1.18 | 29.9 | 39.2 | 0.95 | 26.5 | 32.1 |
| 11380 | Horse grooming | 6.0 | 1.58 | 36.6 | 54.6 | 1.26 | 31.1 | 41.9 |
| 11390 | Horse racing, galloping | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11400 | Horse racing, trotting | 6.5 | 1.71 | 39.2 | 61.0 | 1.37 | 32.9 | 45.7 |

**Table A.4. MET Intensities and Estimates of Ventilation for Occupational Activities Listed in the Compendium of Physical Activities (2000) (Continued)**

| | | | Males | | | Females | | |
|---|---|---|---|---|---|---|---|---|
| | | | | $\dot{V}_E$ (L·min$^{-1}$) | | | $\dot{V}_E$ (L·min$^{-1}$) | |
| *Code* | *Description* | *METs* | $\dot{V}O_2$ $^A$ (L·min$^{-1}$) | *Hagan & Smith* | *Baba* | $\dot{V}O_2$ $^B$ (L·min$^{-1}$) | *Hagan & Smith* | *Baba* |
| 11590 | Sitting; moderate (heavy levers, riding mower/forklift, crane operation), teaching stretching or yoga | 2.5 | 0.66 | | 25.2 | 0.53 | | 22.5 |
| 11600 | Standing; light (bartending, store clerk, assembling, filing, duplicating, putting up a Christmas tree), standing and talking at work, changing clothes when teaching physical education | 2.3 | 0.60 | | 24.1 | 0.48 | | 21.8 |
| 11610 | Standing; light/moderate (assemble/repair heavy parts, welding, stocking, auto repair, pack boxes for moving, etc.), patient care (as in nursing) | 3.0 | 0.79 | | 28.1 | 0.63 | | 24.6 |
| 11615 | Lifting items continuously, 10-20 lbs., with limited walking or resting | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11620 | Standing; moderate (assembling at fast rate, intermittent, lifting 50 lbs., hitch/twisting ropes) | 3.5 | 0.92 | 26.1 | 31.4 | 0.74 | | 26.9 |
| 11630 | Standing; moderate/heavy (lifting more than 50 lbs., masonry, painting, paper hanging) | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11640 | Steel mill, fettling | 5.0 | 1.31 | 32.0 | 43.8 | 1.05 | 27.9 | 35.1 |
| 11650 | Steel mill, forging | 5.5 | 1.44 | 34.2 | 48.9 | 1.16 | 29.5 | 38.3 |
| 11660 | Steel mill, hand rolling | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11670 | Steel mill, merchant mill rolling | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11680 | Steel mill, removing slag | 11.0 | 2.89 | 72.0 | | 2.31 | 53.5 | |
| 11690 | Steel mill, tending furnace | 7.5 | 1.97 | 44.8 | 76.0 | 1.58 | 36.6 | 54.6 |
| 11700 | Steel mill, tipping molds | 5.5 | 1.44 | 34.2 | 48.9 | 1.16 | 29.5 | 38.3 |
| 11710 | Steel mill, working in general | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11720 | Tailoring, cutting | 2.5 | 0.66 | | 25.2 | 0.53 | | 22.5 |
| 11730 | Tailoring, general | 2.5 | 0.66 | | 25.2 | 0.53 | | 22.5 |
| 11740 | Tailoring, hand sewing | 2.0 | 0.53 | | 22.5 | 0.42 | | 20.6 |
| 11750 | Tailoring, machine sewing | 2.5 | 0.66 | | 25.2 | 0.53 | | 22.5 |
| 11760 | Tailoring, pressing | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11765 | Tailoring, weaving | 3.5 | 0.92 | 26.1 | 31.4 | 0.74 | | 26.9 |
| 11766 | Truck driving, loading and unloading truck (standing) | 6.5 | 1.71 | 39.2 | 61.0 | 1.37 | 32.9 | 45.7 |
| 11770 | Typing, electric, manual or computer | 1.5 | 0.39 | | 20.2 | 0.32 | | 18.9 |

**Table A.4. MET Intensities and Estimates of Ventilation for Occupational Activities Listed in the Compendium of Physical Activities (2000) (Continued)**

| | | | Males | | | Females | | |
|---|---|---|---|---|---|---|---|---|
| | | | | $\dot{V}_E$ (L·min$^{-1}$) | | | $\dot{V}_E$ (L·min$^{-1}$) | |
| Code | Description | METs | $\dot{V}_{O_2}$ [A] (L·min$^{-1}$) | Hagan & Smith | Baba | $\dot{V}_{O_2}$ [B] (L·min$^{-1}$) | Hagan & Smith | Baba |
| 11780 | Using heavy power tool such as pneumatic tools (jackhammers, drills, etc.) | 6.0 | 1.58 | 36.6 | 54.6 | 1.26 | 31.1 | 41.9 |
| 11790 | Using heavy tools (not power) such as shovel, pick, tunnel bar, spade | 8.0 | 2.10 | 48.0 | 84.9 | 1.68 | 38.6 | 59.6 |
| 11791 | Walking on job, less than 2.0 mph (in office or lab area), very slow | 2.0 | 0.53 | | 22.5 | 0.42 | | 20.6 |
| 11792 | Walking on job, 3.0 mph, in office, moderate speed, not carrying anything | 3.3 | 0.87 | | 30.0 | 0.69 | | 26.0 |
| 11793 | Walking on job, 3.5 mph, in office, brisk speed, not carrying anything | 3.8 | 1.00 | 27.2 | 33.6 | 0.80 | | 28.4 |
| 11795 | Walking, 2.5 mph, slowly and carrying light objects less than 25 pounds | 3.0 | 0.79 | | 28.1 | 0.63 | | 24.6 |
| 11796 | Walking, gathering things at work, ready to leave | 3.0 | 0.79 | | 28.1 | 0.63 | | 24.6 |
| 11800 | Walking, 3.0 mph, moderately and carrying light objects less than 25 lbs. | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11805 | Walking, pushing a wheelchair | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11810 | Walking, 3.5 mph, briskly and carrying objects less than 25 pounds | 4.5 | 1.18 | 29.9 | 39.2 | 0.95 | 26.5 | 32.1 |
| 11820 | Walking or walk downstairs or standing, carrying objects about 25 to 49 pounds | 5.0 | 1.31 | 32.0 | 43.8 | 1.05 | 27.9 | 35.1 |
| 11830 | Walking or walk downstairs or standing, carrying objects about 50 to 74 pounds | 6.5 | 1.71 | 39.2 | 61.0 | 1.37 | 32.9 | 45.7 |
| 11840 | Walking or walk downstairs or standing, carrying objects about 75 to 99 pounds | 7.5 | 1.97 | 44.8 | 76.0 | 1.58 | 36.6 | 54.6 |
| 11850 | Walking or walk downstairs or standing, carrying objects about 100 pounds or over | 8.5 | 2.23 | 51.3 | | 1.79 | 40.8 | 65.1 |
| 11870 | Working in scene shop, theater actor, backstage employee | 3.0 | 0.79 | | 28.1 | 0.63 | | 24.6 |
| 11875 | Teach physical education, exercise, sports classes (non-sport play) | 4.0 | 1.05 | 27.9 | 35.1 | 0.84 | | 29.4 |
| 11876 | Teach physical education, exercise, sports classes (participate in the class) | 6.5 | 1.71 | 39.2 | 61.0 | 1.37 | 32.9 | 45.7 |

[A] Assuming a body weight of 75 kg
[B] Assuming a body weight of 60 kg