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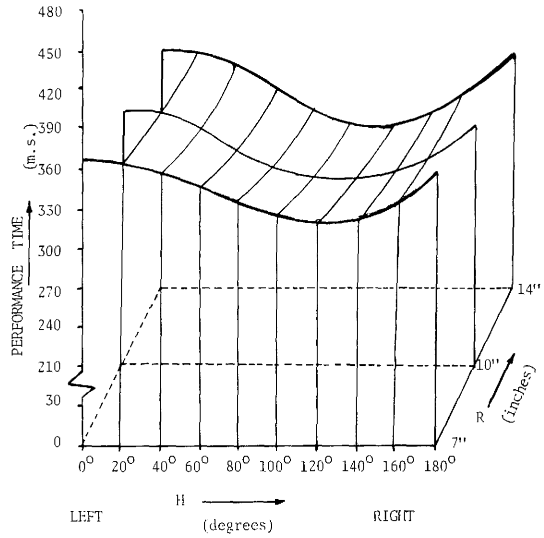

Figure 3 — H and R vs. mean performance time.

Respiratory responses of coal miners for use with mechanical simulators

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The respiratory responses of forty-four coal miners were measured while performing tasks which simulated mine escape and rescue activities. Relationships of oxygen consumption to pulmonary ventilation, respiration frequency, tidal volume, and carbon dioxide elimination were determined. In order to specify the respiratory parameters for a mechanical breathing simulator, the rate of oxygen consumption is proposed as the independent variable from which the other metabolic variables may be calculated. The use of these results for the simulation of respiratory responses on a mechanical simulator are discussed.

introduction

The Bureau of Mines has been engaged in a program to develop new and improved life support and rescue technology to ensure that miners will survive a disaster. A major part of this program involves the design, development, and testing of self-contained breathing apparatus for both escape and rescue missions. As part of its evaluation procedure, the Bureau subjects a newly developed breathing apparatus to a rigorous machine and man test program.

The Bureau conducts machine tests using an Automated Breathing Metabolic Simulator (ABMS).[1] The ABMS is capable of simulating the pulmonary responses of a working man by duplicating ventilation rate, breathing frequency, tidal volume, oxygen consumption, and carbon dioxide production for a sequence of different work tasks. The use of machine testing allows for specific and controlled test conditions.

To accurately test an apparatus, however, the simulator must be programmed to simulate expected O_2 uptake, CO_2 output, and ventilatory responses a man would have while actually using the apparatus. Furthermore, metabolic information must be provided to the breathing machine for a variety of men performing similar tasks, so that the simulator can duplicate a range of values (e.g., 50 percentile and 95 percentile responses).

In order to provide the required information to properly simulate metabolic demands, a series of man-tests, which included activities designed to simulate expected escape and rescue tasks, were performed using Pennsylvania underground coal miners. The results of these tests, and how the results can be used for a breathing simulator are the subjects of this report.

methods

Forty-four underground coal miners participated in this study. Sixteen of the men were studied at sub-maximal levels of work, while the remaining 28 men were involved in exhausting work. The ages of the men were uniformly distributed and their mean and range of ages and weights are given in Table I.

The first group of 16 men performed tasks designed to simulate rescue activities. The men wore ordinary work clothes. The work tasks were shovelling, arm cranking, walking, and carrying a 14 kg cement block. Each task lasted five to six minutes. The subject breathed through a two-way breathing valve so that he inspired room air and expired into a mixing chamber followed by a dry gas meter. The levels of oxygen and carbon dioxide in the mixing chamber were continuously monitored. The pulmonary responses were measured and the participant was allowed to rest for ten minutes before the next task. Usually the men would complete nine tasks in one day's session.

TABLE I
Physical Characteristics for the Two Groups of Miners

Test Subjects	Mean	Range
Group One (N = 16)		
Age (years)	43	21 - 62
Weight (kg)	86	70 - 113
Group Two (N = 28)		
Age (years)	34	18 - 56
Weight (kg)	81	55 - 99
$\dot{V}_{O_2}$ maximum (L/min)	3.4	2.4 - 4.8

During the shovelling task, the miners lifted simulated coal from the floor-level container into a bin one meter high. A chute at the bottom allowed the coal to return to the container for the next shovel load. The rate of shovelling (loads per minute) and the weight per load were selected to give work rates of 50, 70, 90 and 110 kp · m/min. Arm cranking was performed at 200, 300, and 400 kp · m/min. Walking at 4.8 km/hr at a grade of 2.5% was the walking task. The carrying task had alternating carrying/walking intervals of 0.5 and 1.0 minutes on a level treadmill at 4.0, 4.8, and 5.6 km/hr. During the carrying interval, the man would hold a 14 kg cement block. There were 178 tasks performed by the 16 men during which pulmonary ventilation, respiration frequency, oxygen uptake, and carbon dioxide elimination were measured. There were an additional 65 tasks during which time the respiratory frequency was not measured because the necessary equipment was not available.

The second group of 28 coal miners were subjected to a stress test to evaluate fitness during escape activities. The participants were dressed in loose fitting shorts and wore rubber soled shoes. The work was treadmill walking at 4.8 km/hr while the slope of the treadmill was increased from 5% to 20% in 2.5% increments at two minute intervals. When the man felt that he was unable to continue for more than one minute, his expired air through a two-way breathing valve was collected in a Douglas bag and used to determine pulmonary ventilation, oxygen uptake, and carbon dioxide elimination at the exhausting work rate. There was one set of measurements for each of the 28 men. The mean and range of peak oxygen consumptions are given in Table I for Group Two.

In all cases, the pulmonary ventilation, oxygen uptake, and carbon dioxide elimination were reduced to standard temperature (0°C) and pressure (760 mmHg), dried (STPD) in order to report the results in a standard notation.[2] The mathematical relationships between oxygen uptake ($\dot{V}_{O_2}$) and pulmonary ventilation ($\dot{V}_E$), respiration frequency (RF), tidal volume (TV), and carbon dioxide elimination ($\dot{V}_{CO_2}$) were determined by testing linear regression, multiple linear regression, and a number of nonlinear equations to fit the data. In addition to the respiratory variables, age and weight were considered as possible factors. The Biomedical Computer Programs[3] were used to calculate the best coefficients for each type of equation and provide the standard error of estimate (SEE). The SEE is the measure of dispersion of the data about the equation used to describe the relationship and is analogous to the standard deviation about a mean. In fitting equations to the experimental data it is desirable to minimize the SEE.

results and discussion

The level of physical fitness was not directly assessed for the first group of miners. For each of these men, the data for heart rate versus oxygen consumption were plotted and the line was extrapolated to the age expected maximal heart rate. The maximum oxygen consumptions estimated in this manner fell into the range of values found for the second group of coal miners. The two groups were assumed to be typical of coal miners in terms of their pulmonary responses to work.

respiratory variables as a function of oxygen uptake

For any given type of work, the oxygen consumption increases with increasing work rate. While it is relatively easy to quantify external work performed for shovelling or cranking, it is more difficult for walking. In addition, the oxygen cost per unit of work is much greater for shovelling than it is for cranking. Because of the difficulties of relating oxygen cost and other respiratory variables with work rate, the pulmonary responses were described as a function of the metabolic cost (oxygen consumption) instead of the amount of external work.

The data were examined in two groups. The first group contained all of the metabolic data for both the simulated rescue activities (submaximal work rates) and the exhausting (maximal) work rates. The second group contained data for sub-maximal work rates only. This was done to determine if better fits were obtainable over smaller ranges of work rates.

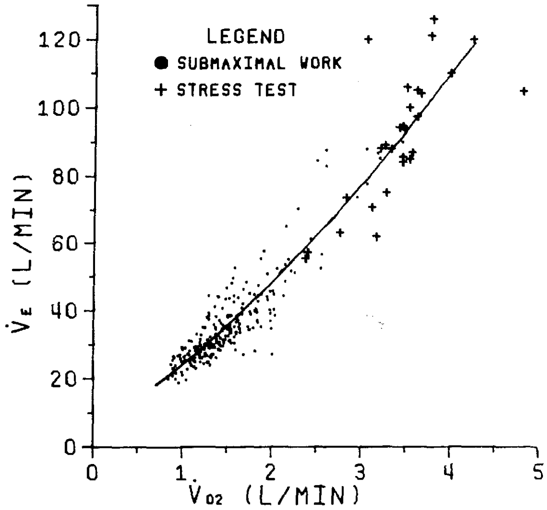

Figure 1 — Nonlinear curve used to describe the relationship of $\dot{V}_E$ to $\dot{V}_{O_2}$.

$\dot{V}_E$ vs $\dot{V}_{O_2}$

Equation 1 describes the best relationship of $\dot{V}_E$ to $\dot{V}_{O_2}$.

$$\dot{V}_E = 8.35 + 15.7\ \dot{V}_{O_2}^{1.35} \quad (1)$$

The SEE is 6.9 L/min. The equation and data are illustrated in Figure 1.

The SEE can be reduced to 6.6 L/min by including an age adjusted intercept which accounts for a tendency of those over 40 years to be above the line. The age adjusted intercept adds to the complexity of the equation while providing only a 4% decrease in the SEE.

If the submaximal data is analyzed alone, the SEE can be lowered to about 5 L/min but the equations predict essentially the same values as Equation 1 in the range of 0.5 to 2.0 L_{O_2}/min. The higher SEE for Equation 1 is therefore due to the greater dispersion of the data above a $\dot{V}_{O_2}$ of 2.0 L_{O_2}/min. This is expected as the maximal work rate is approached.[4]

$\dot{V}_{CO_2}$ vs $\dot{V}_{O_2}$

The carbon dioxide elimination also displayed a nonlinear relationship to oxygen uptake.The

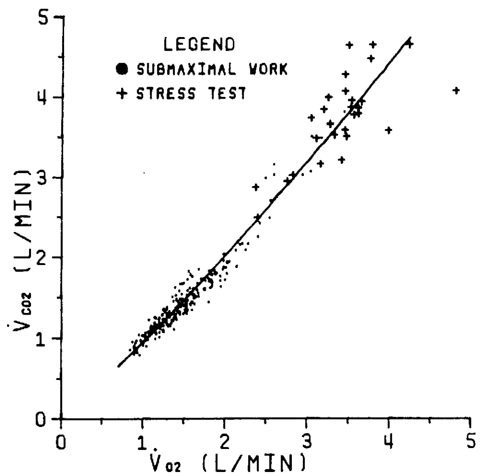

Figure 2 — Nonlinear curve used to describe the relationship of $\dot{V}_{CO_2}$ to $\dot{V}_{O_2}$.

relationship is described by Equation 2.

$$\dot{V}_{CO_2} = 0.094 + 0.846 \cdot \dot{V}_{O_2}^{1.18} \quad (2)$$

The SEE is 0.18 L/min. The equation and data are shown in Figure 2.

The SEE could not be improved with adjustments for age and/or weight. For the submaximal data a linear relationship provided a SEE of 0.09 L/min; but, as in the case of $\dot{V}_E$, the difference from equation 2 was small for $\dot{V}_{O_2}$ less than 2.0 L/min. Again the large SEE is due to increased dispersion of the data above 2.0 L_{O_2}/min.

The gas exchange ratio ($\dot{V}_{CO_2}/\dot{V}_{O_2}$) increases from 0.94 at $\dot{V}_{O_2}$ = 1.0 L/min to 1.09 at 3.5 L/min. These values suggest that the participants were not in a physiological steady state. This would be especially true for the second group of men who performed exhausting work. The data, however, approximate the pulmonary responses which would be expected from a miner performing escape and rescue activities.

respiratory variables as a function of oxygen uptake

Both respiration frequency (RF) and tidal volume (TV) displayed very little correlation with any other respiratory parameter; and age and weight factors did not improve the fits. The linear regressions on $\dot{V}_{O_2}$ are:

$$RF = 17.4 + 6.7\,\dot{V}_{O_2} \quad (3)$$

$$TV = 0.67 + 0.43\,\dot{V}_{O_2} \quad (4)$$

The SEEs are 4.8 for Equation 3 and 0.26 for Equation 4.

The product of RF times TV is the pulmonary ventilation, $\dot{V}_E$, by definition. If the values for RF and TV from Equations 3 and 4 are multiplied together at a given $\dot{V}_{O_2}$ less than 3.0 L/min, the value does agree well with the value for $\dot{V}_E$ predicted by Equation 1 at the same $\dot{V}_{O_2}$. The product of estimated RF's and TV's deviates from the predicted $\dot{V}_E$ above 3.0 L/min because of the linear equations for RF and TV. The best procedure is to select a specific $\dot{V}_E$ and either RF or TV can be calculated from Equation 3 or 4, respectively, and then the other parameter is computed from $\dot{V}_E$. For example, if $\dot{V}_E$ = 50 and TV = 2 then RF = 25.

machine testing

The above equations can be used to set the respiratory parameters on a mechanical breathing simulator. First, the metabolic demand of the test is chosen by selecting a $\dot{V}_{O_2}$. Then Equations 1 and 2 are used to determine $\dot{V}_E$ and $\dot{V}_{CO_2}$. Finally, either RF or TV is determined from either Equation 3 or 4 and the other can be calculated.

The volumes of gases are reported for standard conditions. Since the actual tests are usually not performed under standard conditions, a correction factor (CF) must be used to change the volumes. The correction factor given in Equation 5 was derived from the Ideal Gas Law and accounts for changes in volume due to temperature, pressure, and the addition of water vapor.

$$CF = \frac{(273+T)}{273}\;\frac{(760)}{(P_B - P_{H_2O})} \quad (5)$$

where: T = temperature of metabolic gases, °C;
P_{H_2O} = partial pressure of water vapor in the metabolic gases, mmHg; and
P_B = ambient barametric pressure, mmHg.

CF is used to multiply the STPD gas volumes provided in this paper to give the gas volume at the test conditions chosen for the experiment. In the case of the ABMS used by the Bureau of Mines, the typical test conditions for the expired gases are 37°C, ambient pressure (about 740 mmHg) and saturated with water vapor (P_{H_2O} = 47 mmHg). Therefore, the expired tidal volume (TV) and ventilation ($\dot{V}_E$) are multiplied by 1.25 to give the volumes as they would be measured at the test conditions. Because the volume of oxygen removed from the gases and the volume of carbon dioxide added due to the metabolic processes are dry, the value for P_{H_2O} is zero and the correction factor for $\dot{V}_{CO_2}$ at the test conditions is 1.17. In effect, the difference between CF's accounts for the addition of water vapor in the total volume. In the above case, if the oxygen and carbon dioxide volumes were measured when saturated with water vapor they would have to be reduced by a factor of $1.17/1.25 = 0.94$ for dry gas volumes applicable to the ABMS.

Each of the relationships in Equations 1 to 4 has a standard error of estimate associated with it. In order to calculate a respiratory variable ($\dot{V}_E$, TV, RF, or $\dot{V}_{CO_2}$) at a given $\dot{V}_{O_2}$ such that it is expected to be greater than 95% of the observed values, the product of 1.65 times the SEE should be added to the value of the equation at the specified $\dot{V}_{O_2}$. As an example, at $\dot{V}_{O_2} = 1.5$ L/min, $\dot{V}_E = 35.5$; but to include 95% of the expected values, 11.4 (=1.65 x 6.9) L/min must be added. Therefore, 95% of the $\dot{V}_E$'s expected will be less than 46.9 L/min. It should be remembered that once any two of the $\dot{V}_E$, TV, and RF parameters are set, the third value is also established.

By using machine tests, there is a degree of controlled flexibility which cannot be duplicated in man tests. The test conditions can be chosen such that one or two variables are at a 95 percentile level while the others are at a 50 percentile level. In this manner specific components of an apparatus can be examined. As an example, machine tests of breathing apparatus can have respiratory quotients, RQ ($\dot{V}_{CO_2}/\dot{V}_{O_2}$), greater than 1.0, especially if the 95 percentile $\dot{V}_{CO_2}$'s are used. It is not likely that a man can sustain an RQ greater than 1.0 for more than 15 minutes. For machine testing a closed circuit apparatus, on the other hand, an $RQ > 1.0$ would place the CO_2 scrubber under a greater stress than the oxygen source. Thus the failure mode of the scrubber could be determined.

Changes in the pulmonary ventilation waveform have been observed for different individuals, different work rates, and different breathing resistances.[5] The piston waveform of most breathing machines, however, cannot be adjusted during a test. If the waveform remains constant during the machine test, the peak flow rate will be the same for any given $\dot{V}_E$ independent of the RF or TV if a rigid cylinder/piston (or other truly positive displacement system) is used. This is not the case for flexible bellows air movers. For example, for a $\dot{V}_E$ of 50 L/min, the peak flow rate will be the same if RF = 25 and TV = 2 or if RF = 20 and TV = 2.5. Moreover, the peak resistance to breathing will also be the same. Therefore, for positive displacement machines with a fixed waveform and tidal volume, no sacrifice is made for adjusting pulmonary ventilation through respiration frequency.

The above test procedures are also valid for open circuit breathing apparatus systems although the more critical measurements (e.g., the function of the demand regulator) may differ. In addition, the procedures may be used for other breathing devices such as air-purifying respirators.

summary

Equations have been developed from man test data for the estimation of $\dot{V}_E$, RF, TV, and $\dot{V}_{CO_2}$ from $\dot{V}_{O_2}$. In order to use these equations for machine evaluation of breathing apparatus, the test conditions are first specified as the required oxygen consumption ($\dot{V}_{O_2}$). The $\dot{V}_{O_2}$ is then used to specify the remaining respiratory parameters. A correction factor is necessary to change the standard volumes of gases to the prevailing conditions.

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