Respiratory calorimetry is the generally accepted method of estimating the metabolic cost of muscular activity. It requires measuring the pulmonary ventilation and analysing the composition of the expired air. The procedure is time consuming. This method can not be used where large number of measurements are to be taken as in field surveys. Also, this method interferes with the performance of the activity since the person has to wear the face mask or mouthpiece, tubing and portable gasmeter or Douglas bag. So simple techniques for the estimation of energy expenditure rate are required for situations in which simplicity and rapidity of measurement are important or in which the respiratory method can not be used.

Many researchers have developed linear regression equations which relate the energy expenditure rate to some other physiological variable that can easily be measured. Andrews (1967) has suggested the use of different regression equations for different work categories (ie arm work, arm and leg work etc.) in estimating the energy expenditure rate from incremental measures of heart rate (work pulse). Givoni and Goldman (1971) have developed an emperical
equation for predicting metabolic energy expenditure during level or grade walking, with and without loads.

Frederik (1959) has determined oxygen consumption for lifting different loads at four different height levels. This model is not applicable for estimating oxygen consumption for repetitive lifting. Garg (1976) has developed regression models for predicting metabolic rate for specific task conditions.

Thus, a simple methodology to estimate the metabolic cost of all classes of lifting activities is lacking. However, Bernard et al (1979) have developed a nonlinear equation for estimating oxygen consumption from pulmonary ventilation for manually performed activities. They have used an extensive data base from several different activities, such as walking and running at different speeds, carrying 14Kg. in the hands at waist height, crawling on hands and knees, ergometer pedaling, arm cranking, shoveling etc., to develop the model. And it is not known whether data from manual lifting activities are considered. To the author's knowledge, no such studies are available for Indian conditions.

Determination of pulmonary ventilation, an index of work load and also a basis for estimating oxygen consumption, involves a time consuming, difficult and cumbersome measurement process, especially in practical
working situations. Very few attempts have been made to estimate pulmonary ventilation for lifting activities from easily and quickly measurable parameters.

In this chapter two experiments are discussed. First one is related to the validation of Bernard's equation for manual lifting tasks. Second one is concerned with the development of an equation for estimating pulmonary ventilation.

4.1 EXPERIMENT 1 : VERIFICATION OF THE MODEL BY BERNARD et al FOR MANUAL LIFTING TASKS

4.1.1 Introduction

Bernard's equation was used by Babo et al (1983) for estimating the energy expenditure rate of different activities performed by low seam coal miners. However, it is not known whether this equation can also be used for estimating the energy expenditure rate of lifting activities. The purpose of this experiment is to use Indian subjects to lift different loads and measure oxygen consumption and then compare these measured values with the estimated values from the model given by Bernard et al (1979) to validate the model for manual lifting tasks.
4.1.2 Experimental Protocol: Design and Procedure

4.1.2.1 Subjects

Twenty four male subjects have been used in this experiment. They are all young college students. Their ages range from 19-20 years (mean 21.3), their heights range from 158 to 181cm (mean=171.9) and their weights range from 45 to 73 Kg. (mean = 57.2). All the subjects are found to be physically fit for the lifting task and are reported to have never suffered in the past from cardiovascular or musculoskeletal problems. All the subjects are given some practice to familiarize with the lifting task before the observations are taken.

4.1.2.2 Experimental design

The subjects are asked to lift a container (45.5x25.5x26cm) with handles from floor to a shelf height of 51cm using free style lifting technique. The loads ranging from 10 to 20Kg. are lifted at three different frequencies (2,4,and 6 lifts/min). The work loads (load lifted x frequency x height of lift, Kgm/min) are assigned to the subjects depending on their willingness to accept those loads. Oxygen consumption is measured for all the subjects. The frequency count is made using a stop watch. The subjects are required only to lift the load. Lowering the load to the floor level is done by a helper.
4.1.2.3 Procedure

Respiratory measurements are made using MAXPLANK Respiration Gasmeter. The meter is mounted on the back of the subject. Use of the gasmeter by the subject is shown in Plate 1 (Figure 4.1a). Initially the subject is asked to breath into the gasmeter to fill the dead space and/or to flush out the previous air contents. After at least 6 minutes of working when the subject reaches a steady state condition, he is asked to breath again into the gasmeter. The initial gasmeter reading and temperature are noted and the subject is asked to continue breathing into the meter for at least 3 minutes. A sample of 0.6% of the expired air is allowed to be collected into the rubber gas bladder attached to the gasmeter while the subject is working and breathing into the meter. At the end, the duration of gas collection, the final gasmeter reading and temperature are noted. The gasmeter is dismounted from the subject. The rubber bladder is removed and its mouth is clamped tightly. The barometric pressure during the experiment is also recorded. Pulmonary ventilation in litres per minute (STPD) is calculated using the following equation.

\[ VE = [(V_2 - V_1) + 0.6\%(V_2 - V_1)] \times C \times \text{STPD factor} \]

where \( VE = \) Pulmonary ventilation in litres/min at Standard Temperature Pressure Dry (STPD)

\( V_1 = \) Initial gasmeter reading (litres)
\[ V_2 = \text{Final gasmeter reading (litres)} \]
\[ C = \text{Gasmeter constant } = 1.00942 \]
\[ T = \text{Time duration of gas collected in minutes} \]

STPD factor corresponding to the temperature and barometric pressure during the experiment is obtained from readily available line chart (Consolazio et al, 1963). The line chart is shown in Figure 4.2.

In order to determine the oxygen consumption by the subject during lifting, the expired air sample (collected in the rubber bladder) is analysed to determine the carbondioxide and oxygen contents using Orsat apparatus (Plate 1 - Figure 4.1b). The following equation (Consolazio et al, 1963) is used to determine the oxygen consumption from the results of gas analysis.

\[ V_{O2} = \frac{(V_E)}{100}(\%N_2 \times 0.265 - \%O_2) \text{ litres/min.} \]

Where \( V_{O2} = \text{Oxygen consumption in litres/min (STPD)} \).
\( V_E = \text{Pulmonary ventilation in litres/min (STPD)} \).
\( \%N_2 = \text{Percentage of nitrogen in the expired air} \).
\( \%O_2 = \text{Percentage of oxygen in the expired air} \).
\[ V_2 = \text{Final gasmeter reading (litres)} \]
\[ C = \text{Gasmeter constant } = 1.00942 \]
\[ T = \text{Time duration of gas collected in minutes} \]

STPD factor corresponding to the temperature and barometric pressure during the experiment is obtained from readily available line chart (Consolazio et al, 1963). The line chart is shown in Figure 4.2.

In order to determine the oxygen consumption by the subject during lifting, the expired air sample (collected in the rubber bladder) is analysed to determine the carbondioxide and oxygen contents using Orsat apparatus (Plate 1 -Figure 4.1b). The following equation (Consolazio et al, 1963) is used to determine the oxygen consumption from the results of gas analysis.

\[ V_{O2} = \frac{V_E}{100}(N_2 \times 0.265 - O_2) \text{ litres/min.} \]

Where \( V_{O2} = \text{Oxygen consumption in litres/min (STPD)} \).
\( V_E = \text{Pulmonary ventilation in litres/min (STPD).} \)
\( N_2 = \text{Percentage of nitrogen in the expired air.} \)
\( O_2 = \text{Percentage of oxygen in the expired air.} \)
FIGURE 4.2: LINE CHART FOR DETERMINING FACTORS TO REDUCE SATURATED GAS VOLUMES TO DRY VOLUMES AT 0°C AND 760 MM Hg (CONSOLAZIO et al, 1963)

Example: Temperature = 24°C
Borometric Pressure = 750 mm Hg
STPD factor = 0.880
The following equations are used to determine the carbondioxide and the oxygen contents in the expired air sample.

\[
\% \text{CO}_2 = \frac{V_3 - V_2}{V_1 - V_2} \times 100
\]

\[
\% \text{O}_2 = \frac{V_4 - V_3}{V_1 - V_2}
\]

\[
\% \text{N}_2 = 100 - (\% \text{CO}_2 + \% \text{O}_2)
\]

Where

- \( V_1 = 100 \text{ml} \)
- \( V_2 = \text{Volume after air sample intake} \)
- \( V_3 = \text{Volume after CO}_2 \text{ absorption} \)
- \( V_4 = \text{Volume after O}_2 \text{ absorption} \)

\( \text{VO}_2 \) is also estimated separately, for all the 24 subjects from the following equation developed by Bernard et al (1979), using the pulmonary ventilation value and the subject's age.

\[
0.44 \text{VO}_2 = (0.69 - 0.002A) \times \text{VE} - 1.47
\]

Where \( \text{VO}_2 = \text{Oxygen consumption in litres/min(STPD)} \)

- \( \text{VE} = \text{Expired air volume in liters/min(STPD)} \)
- \( A = \text{Age of the subject in years} \)

The measured values of pulmonary ventilation, oxygen consumption and the estimated values of oxygen consumption for the 24 subjects are given in Table 4.1.
The following equations are used to determine the carbon dioxide and the oxygen contents in the expired air sample.

\[
\frac{V_3-V_2}{V_1-V_2} \times 100 = \%CO_2
\]

\[
\frac{V_4-V_3}{V_1-V_2} = \%O_2
\]

\[
\%N_2 = 100-(\%CO_2+\%O_2)
\]

Where

- \( V_1 = 100\text{ml} \)
- \( V_2 \): Volume after air sample intake
- \( V_3 \): Volume after CO2 absorption
- \( V_4 \): Volume after O2 absorption

\( \text{VO}_2 \) is also estimated separately, for all the 24 subjects from the following equation developed by Bernard et al (1979), using the pulmonary ventilation value and the subject's age.

\[
\text{VO}_2 = \left(0.69 - 0.002A\right) \times \text{VE} - 1.47
\]

Where

- \( \text{VO}_2 \): Oxygen consumption in litres/min(STPD)
- \( \text{VE} \): Expired air volume in liters/min(STPD)
- \( A \): Age of the subject in years

The measured values of pulmonary ventilation, oxygen consumption and the estimated values of oxygen consumption for the 24 subjects are given in Table 4.1.
<table>
<thead>
<tr>
<th>S. No.</th>
<th>VE(STPD) litres/min.</th>
<th>Measured VO₂(STPD) Litres/min</th>
<th>Estimated VO₂(STPD) from Bernard's Eqn. litres/Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>11.22</td>
<td>0.323</td>
<td>0.384</td>
</tr>
<tr>
<td>2.</td>
<td>12.19</td>
<td>0.466</td>
<td>0.453</td>
</tr>
<tr>
<td>3.</td>
<td>11.41</td>
<td>0.473</td>
<td>0.427</td>
</tr>
<tr>
<td>4.</td>
<td>16.05</td>
<td>0.667</td>
<td>0.734</td>
</tr>
<tr>
<td>5.</td>
<td>14.95</td>
<td>0.602</td>
<td>0.667</td>
</tr>
<tr>
<td>6.</td>
<td>12.71</td>
<td>0.528</td>
<td>0.519</td>
</tr>
<tr>
<td>7.</td>
<td>20.79</td>
<td>0.826</td>
<td>0.970</td>
</tr>
<tr>
<td>8.</td>
<td>20.22</td>
<td>0.937</td>
<td>0.971</td>
</tr>
<tr>
<td>9.</td>
<td>19.64</td>
<td>0.847</td>
<td>0.932</td>
</tr>
<tr>
<td>10.</td>
<td>13.02</td>
<td>0.419</td>
<td>0.541</td>
</tr>
<tr>
<td>11.</td>
<td>15.05</td>
<td>0.834</td>
<td>0.679</td>
</tr>
<tr>
<td>12.</td>
<td>14.64</td>
<td>0.675</td>
<td>0.621</td>
</tr>
<tr>
<td>13.</td>
<td>15.63</td>
<td>0.641</td>
<td>0.689</td>
</tr>
<tr>
<td>14.</td>
<td>12.44</td>
<td>0.590</td>
<td>0.501</td>
</tr>
<tr>
<td>15.</td>
<td>11.57</td>
<td>0.559</td>
<td>0.428</td>
</tr>
<tr>
<td>16.</td>
<td>13.39</td>
<td>0.519</td>
<td>0.565</td>
</tr>
<tr>
<td>17.</td>
<td>18.04</td>
<td>0.721</td>
<td>0.851</td>
</tr>
<tr>
<td>18.</td>
<td>18.03</td>
<td>0.880</td>
<td>0.850</td>
</tr>
<tr>
<td>19.</td>
<td>23.15</td>
<td>1.042</td>
<td>1.112</td>
</tr>
<tr>
<td>20.</td>
<td>21.13</td>
<td>1.022</td>
<td>1.010</td>
</tr>
<tr>
<td>21.</td>
<td>21.37</td>
<td>1.143</td>
<td>1.023</td>
</tr>
<tr>
<td>22.</td>
<td>15.48</td>
<td>0.650</td>
<td>0.700</td>
</tr>
<tr>
<td>23.</td>
<td>18.64</td>
<td>0.697</td>
<td>0.848</td>
</tr>
<tr>
<td>24.</td>
<td>17.14</td>
<td>0.571</td>
<td>0.792</td>
</tr>
</tbody>
</table>

Mean 16.16 0.693 0.719
Std. Dvn. 3.60 0.210 0.216
4.1.3 Results and Discussion

It is found that the estimated VO2 from Bernard's model has a very high correlation (r=0.88) with the measured values of oxygen consumption. Thus, this experiment shows that Bernard's model for estimating oxygen consumption rate, developed for tasks other than lifting, can also be applied to lifting tasks.

However, it is to be noted that in this experiment student subjects (inexperienced in manual handling) are used. Though experience and training affect manual lifting performance in terms of VE, since Bernard's equation is solely based on VE, experience or inexperience may not be a limiting factor in its applicability.

4.2 EXPERIMENT 2: ESTIMATION OF PULMONARY VENTILATION

4.2.1 Introduction

From the first experiment it is concluded that Bernard's equation can be used to estimate oxygen consumption of manual lifting tasks. This equation is a function of pulmonary ventilation (VE), measurement of which is an involved and cumbersome process as already indicated. The existence of linear relationship between work load and pulmonary ventilation is well established (Lind and Petrofsky, 1978). This linearity can be relied up to moderate work loads (Astrand and Rodahl, 1970). Normally in
industry most of the work loads will be at or below the moderate levels. Presuming these conditions, an experiment is designed to gather data and develop a predictive model for estimating pulmonary ventilation during manual lifting tasks.

4.2.2 Experimental Protocol: Design and Procedure

4.2.2.1 Subjects

Thirty six subjects have participated in this experiment. They include 20 workers experienced in manual handling and 16 college students. Their ages range from 18 to 27 years (mean: 22), body heights range from 150 to 175 cm (mean: 164.9) and body weights range from 36.5 to 76 Kg (mean: 53.4). The subjects are reported to have never experienced any cardiovascular and musculoskeletal problems. The students are given some practice in manual lifting before the experimental observations are made.

4.2.2.2 Experimental design

Eighteen loads (5 to 28 Kg), 10 frequencies (1 to 10 lifts/min), 10 distances of lift (30 to 150 cm) and four heights of lifting (floor to 150 cm, 51-102 cm, 51 - 153 cm and 102 - 153 cm) are selected as independent variables. Thirty work loads are generated by selecting frequency, load and distance of lift randomly for the first lift range (floor to 150 cm). Among these thirty work loads some may be
same, but with a different combination of load, frequency and distance. The distance of lift selected randomly is rounded off to the nearest ten centimeters. For example if the distance selected randomly is 108 cm, it is rounded off as 110 cm. For the other three lift ranges (51-102 cm, 51-153 cm and 102-153 cm), four work loads are selected, which are kept same for all the three lift ranges. Each work load is assigned at least to three different subjects. Thus, totally 126 respiratory measurements (30 work loads x 3 subjects + 4 work loads x 3 subjects x 3 lift ranges = 126) are made. Pulmonary ventilation is the response variable.

4.2.2.3 Procedure

The lifting task consists of lifting a container (45.5x25.5x26 cm) with handles at the specified experimental treatment combination (load, frequency and distance of lift) using free style lifting technique. For each subject and workload treatment combination pulmonary ventilation (VE) is measured as discussed in the preceding experiment.

Mean values of pulmonary ventilation corresponding to various work loads are given in Table 4.2.
TABLE 4.2 WORK LOADS AND THE MEAN VALUES OF PULMONARY VENTILATION (VE)

<table>
<thead>
<tr>
<th>Work load (Kg-m/min)</th>
<th>Pulmonary Ventilation (VE) (Litres/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.6</td>
<td>9.23</td>
</tr>
<tr>
<td>10</td>
<td>10.45</td>
</tr>
<tr>
<td>18</td>
<td>12.19</td>
</tr>
<tr>
<td>20</td>
<td>12.20</td>
</tr>
<tr>
<td>30</td>
<td>15.78</td>
</tr>
<tr>
<td>35</td>
<td>17.59</td>
</tr>
<tr>
<td>40</td>
<td>15.12</td>
</tr>
<tr>
<td>44</td>
<td>19.03</td>
</tr>
<tr>
<td>45</td>
<td>17.53</td>
</tr>
<tr>
<td>48</td>
<td>21.23</td>
</tr>
<tr>
<td>52.8</td>
<td>20.88</td>
</tr>
<tr>
<td>54</td>
<td>18.39</td>
</tr>
<tr>
<td>58.8</td>
<td>18.52</td>
</tr>
<tr>
<td>60</td>
<td>24.57</td>
</tr>
<tr>
<td>64</td>
<td>23.96</td>
</tr>
<tr>
<td>67.2</td>
<td>23.07</td>
</tr>
<tr>
<td>67.5</td>
<td>22.12</td>
</tr>
<tr>
<td>75.6</td>
<td>21.23</td>
</tr>
<tr>
<td>84</td>
<td>26.81</td>
</tr>
<tr>
<td>92.4</td>
<td>22.76</td>
</tr>
<tr>
<td>94.5</td>
<td>24.5</td>
</tr>
<tr>
<td>120</td>
<td>26.90</td>
</tr>
<tr>
<td>144.9</td>
<td>31.45</td>
</tr>
</tbody>
</table>

4.2.3 Results and Discussion

In order to develop a model to predict pulmonary ventilation, multiple linear regression with backward elimination procedure is used. The subject characteristics, and the task characteristics are used as independent variables and the pulmonary ventilation as the dependent variable. The resultant equation which is a function of task characteristics and individual's body weight had a low value of coefficient of determination ($R^2=0.67$). Finally a
simple linear regression between work load (Kg-m/min) and VE is evolved as a better predictive equation. This is given below.

\[ \text{VE} = 10.86 + 0.1542 \times \text{(Work load)} \]

Where VE = Pulmonary ventilation in litres/min (STPD)  
Workload = load x freq x distance of lift (Kg-m/min).

This equation explains about 86% of variation (r=0.93) and the standard error is 2.2 litres/min. The F value is 122.45 which is highly significant.

Pulmonary ventilation during lifting tasks can be estimated using the equation developed in this study. The actual work load associated with lifting tasks prevailing in the industries may be well within the range of values considered in this study. However, the following fact has to be kept in mind when using this equation. Pulmonary ventilation (VE) increases with increasing work loads. The increase is semilinear, with a relatively greater increase at the heavier work loads (Astrand and Rodahl, 1970). Since the industrial work will normally involve moderate levels of work, the present equation can be very useful.
4.3 CONCLUSIONS

The second series of experiments are conducted primarily to suggest a methodology to estimate the metabolic cost of lifting activities easily and quickly, especially under field conditions. The results of this study indicate that the equation developed by Bernard et al (1979) can be readily used for estimating metabolic cost of lifting activities also. Since this equation is based on pulmonary ventilation, the measurement of which is again a time consuming and cumbersome process, an equation is developed to estimate pulmonary ventilation from work load.

The advantage of using this methodology to estimate VO2 is the convenience of not measuring VE and not collecting and analysing gas samples. However, if more specific and accurate metabolic information is necessary, measurement and analysis of the expired air is unavoidable.