Oxygen Uptake during Weaning from Mechanical Ventilation*

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Total body oxygen uptake (VO2) increases during the transition from machine-assisted ventilation to spontaneous breathing. Since the volume of oxygen consumed by the respiratory muscles must contribute to the increase in VO2 (ΔVO2), we explored whether ΔVO2 and/or measurements of respiratory power output (Wresp) provide clinically useful information in the evaluation of disease state and weaning decisions in patients with respiratory failure. We determined the metabolic, ventilatory, and hemodynamic responses of ten patients during weaning from controlled mechanical ventilation, and compared ΔVO2 and Wresp of patients without overt heart-lung disease (group 1) to that of patients with significant cardiopulmonary dysfunction and ventilator-dependent respiratory failure (group 2). We reasoned that for ΔVO2 to be clinically useful, individual values must either clearly differ between groups, must be higher in patients with heart-lung disease, and/or correlate with weaning outcome and independent measurements of respiratory work. The ΔVO2 increased in nine of ten patients. The differences between the groups in the values of ΔVO2 (27 ml/min and 49 ml/min) and respiratory power (9.35 J/min and 11.99 J/min) were not significant. ΔVO2 and Wresp were not correlated (r = 0.2), and neither predicted weaning outcome. We conclude that the sensitivity and specificity of ΔVO2 and Wresp appear insufficient for evaluation of disease state and weaning decisions in individual patients. (Chest 1988; 94:1148-55)

\[ W_{\text{resp}} = \text{respiratory power output}; \ Q = \text{cardiac output}; \ W_{mv/L} = \text{inspiratory work by mechanical ventilator.} \]

Total body oxygen uptake (VO2) varies in proportion to the load placed on the respiratory system. In humans, increases in VO2 have been described during isocapnic hyperpnea,1-8 during inspiratory resistive loading,6,7 and with the transition from machine-assisted ventilation to spontaneous breathing.6-14 In these studies, the increase in VO2 (ΔVO2) has been assumed to be primarily a measure of the energy consumed by the contracting respiratory muscles and is frequently referred to as the oxygen cost of breathing (VO2 Resp).

Respiratory muscle fatigue is widely believed to be a common occurrence in patients with hypercapnic respiratory failure.15 Because fatigue and failure to wean from mechanical ventilation may be determined by an imbalance between the mechanical load on the respiratory muscles and their endurance, a measure of the metabolic energy requirements of respiratory muscles (proportional to load) might be of considerable clinical value. Therefore, we evaluated the metabolic, ventilatory, and hemodynamic responses of patients during weaning from controlled mechanical ventilation, to test whether in this setting ΔVO2 and estimates of inspiratory work could provide clinically useful information.

To assess the clinical utility of ΔVO2 measurements, we compared patients with heart-lung disease and ventilator-dependent respiratory failure to a group without heart-lung disease who underwent an elective abdominal operation and were extubated within 24 hours after the surgical procedure. We reasoned that ventilator-dependent patients with cardiopulmonary diseases have a greater change in metabolic oxygen demand with weaning than otherwise normal subjects following elective surgery. Although this hypothesis has never been tested directly, there is some information available which supports it.12,13 We thought that if this line of reasoning was incorrect, the measurement of ΔVO2 would be insensitive and of limited value in the evaluation of disease state and weaning decisions in individual patients.

Material and Methods

Patient Population

The ages, indications for mechanical ventilation, cardiorespiratory status, pertinent diagnoses, and duration of mechanical ventilation for the ten patients are shown in Table 1. Group 1 consisted of five patients without overt heart-lung disease who underwent an elective abdominal vascular operation and were extubated within 24 hours after the surgical procedure. Group 2 included five patients who suffered from various cardiopulmonary diseases complicated by ventilator-dependent respiratory failure; they all had been ventilated for at least eight days and had failed repeated weaning attempts. All patients were able to sustain gas exchange at least transiently during spontaneous breathing so that steady-state measurements could be obtained (Fig 1).

Methods

Oxygen uptake, carbon dioxide elimination (VCO2), minute ventilation (VE), and end-tidal carbon dioxide tensions (PETCO2) were measured with a metabolic cart (Horizon MMC, SensorMedics).16,17

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Oxygen Uptake during Weaning (Hubmayr et al)
Because small systematic errors in the measurement of inspiratory and expiratory oxygen concentrations can have a large impact on the determination of VO₂, the oxygen sensor of the metabolic cart was equilibrated with the inspiratory gas source for a minimum of 2 h.

Inspiratory gas was provided from Haldane analyzed tanks with oxygen concentrations (FiO₂) of .40 in nine patients and .50 in one patient. Priming the oxygen sensor with inspiratory gas before each measurement improved the accuracy in the operating range and helped to identify sensors that had to be replaced because of excessive drift. In addition, FiO₂ was frequently measured during the experiment, and data were discarded if the measured FiO₂ changed by more than .001. This ensured that systemic errors in VO₂ based on oxygen analyzer drift were less than 5 percent. The VO₂ and VCO₂ values reported in this study are the mean of ten 30-s collections. To minimize random errors, we required that the coefficient of variation in VO₂ when measured during mechanical ventilation was less than 10 percent.

In six patients, cardiac output (Q) was measured with thermodilution. The values reported are the mean of three determinations after the highest and lowest values had been discarded. In these patients, mixed venous oxygen saturation was measured with a COximeter (IL 282). Arterial hemoglobin, oxygen saturation, and blood gas tensions were analyzed using a COximeter and an arterial blood gas instrument (IL 813). Blood oxygen contents were derived using standard equations (Ca×VO₂ = 1.39 × hemoglobin × % saturation + .003 Po₂). A second estimate of oxygen uptake (VO₂p) was calculated from the Fick equation:

\[ \text{VO}_2 = \frac{\text{Q} \times (\text{PaO}_2 - \text{Pao}_2)}{\text{HR} \times \text{RR} \times \text{FIO}_2} \]

Table 1—Clinical Data for the Ten Study Patients

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age, yr</th>
<th>Indication for Mechanical Ventilation</th>
<th>Cardiorespiratory Status</th>
<th>Duration of Mechanical Ventilation, days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>60</td>
<td>Abdominal aortic aneurysm repair</td>
<td>No overt disease, minimal obstruction on spirometry</td>
<td>&lt;1</td>
</tr>
<tr>
<td>2</td>
<td>65</td>
<td>Abdominal aortic aneurysm repair</td>
<td>No overt disease</td>
<td>&lt;1</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>Abdominal aortic aneurysm repair</td>
<td>Status post wedge resection of granuloma, upper lobe</td>
<td>&lt;1</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>Aortobifemoral bypass</td>
<td>No overt disease, normal spirogram</td>
<td>&lt;1</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>Aortotomy and superior mesenteric and celiac endarterectomy</td>
<td>No overt disease, normal spirogram</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Group 2*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>64</td>
<td>Hypercarbic respiratory failure</td>
<td>Sleep apnea, nonspecific demyelinating process</td>
<td>&gt;30</td>
</tr>
<tr>
<td>7</td>
<td>67</td>
<td>Enterolysis for small bowel obstruction</td>
<td>Ischemic heart disease and right ventricular infarction, sepsis</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>59</td>
<td>Abdominal aortic aneurysm repair</td>
<td>Ischemic heart disease, chronic obstructive pulmonary disease</td>
<td>&gt;30</td>
</tr>
<tr>
<td>9</td>
<td>67</td>
<td>Hepatic coma</td>
<td>Alcoholic cardiomyopathy, heart failure</td>
<td>14</td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>Wound debridement</td>
<td>Chronic obstructive pulmonary disease with heart failure</td>
<td>&gt;30</td>
</tr>
</tbody>
</table>

*All patients were able to support an acceptable pulmonary gas exchange during spontaneous breathing for at least 20 min.

![Figure 1](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21586/)
\[ \dot{V}O_2,F = \dot{Q}(CaO_2-CVCO_2). \]

Inspiratory work performed by the ventilator on the relaxed respiratory system (W\text{MV/L}) was derived from the airway pressure signal of a Siemens-Servo 900B ventilator. W\text{MV/L}, expressed in joules per liter, was derived from the peak airway pressure (P\text{PEAK}), the elastic recoil pressure of the system at end-inspiration (PEI), and end-expiratory airway pressure (P\text{EEP}) as follows:

\[ W\text{MV/L} = 1/20 \times (2 \times P\text{PEAK} - P\text{EI} + P\text{EEP}). \]

Some patients received small levels of PEEP (≤6 cm H\text{O}), but PEEP was not applied during spontaneous breathing. Therefore, in our estimate of W\text{MV/L}, the elastic work required to overcome extrinsic PEEP was subtracted. The approximation of inspiratory work by this so-called trapezoid method is valid if inspiratory flow is constant and if the respiratory system comes to a static equilibrium at end-expiration. These conditions were met in our patients, and in preliminary studies we confirmed the observation by Marini et al., who showed an excellent correlation between work determined by the trapezoid method and by conventional pressure-volume integration. The work per minute or power output of the inspiratory muscles (W\text{respiratory}) was estimated from the product of W\text{MV/L} and the spontaneously achieved VE. The limitations and the underlying assumptions of this approach are examined in the Discussion.

**Study Protocol**

The study was approved by the Institutional Review Board, and verbal consent was obtained from all patients. The settings of the Siemens-Servo 900B ventilator were adjusted to suppress all spontaneous respiratory activity. Measurements were made not sooner than 20 min after the inspiratory gas source was switched to Haldane analyzed tanks. For the purpose of this study, steady state was assumed when the respiratory exchange ratio was between .7 and 1.0, when there was no apparent trend with time, and when the coefficient of variation in VO2 obtained from ten 30-s samples was less than 10 percent (Fig 1). At that point, 5-min averages of VO2, VO2, VE, and P\text{ETCO2} were recorded. In addition, ventilator settings, P\text{PEAK}, the end-inflation plateau airway pressure (PEI), P\text{EEP}, cardiac output, arterial hemoglobin concentration, and arterial and mixed venous blood gas values were obtained. After these baseline measurements were determined, mechanical ventilation was discontinued.

During spontaneous breathing, inspiratory gas identical to that used for mechanical ventilation was provided by a meteorologic balloon. Patients breathed through a unidirectional valve attached to the endotracheal tube, and expiratory gas was collected for the on-line analysis of expired volume and gas concentrations from which VO2 was calculated. Once a new steady state was reached, recordings of metabolic, cardiovascular, ventilatory, and gas exchange variables were repeated. All ten patients achieved steady state 15 to 20 minutes after discontinuation of mechanical ventilation (Fig 1). Intermittently during the study, FIO2 was measured to assess systematic errors due to analyzer drift.

**Statistics**

The significance of a weaning-related change in physiologic parameters was evaluated by Student's t tests for paired observations. A change was considered significant at a \( p \) value of <.05. Relationships between different parameters were evaluated with linear regression techniques. Because of the small sample size of individual disease and control groups, conclusions are not based on a statistical evaluation of group mean differences. The power of a test such as \( \Delta VO2 \) or W\text{respiratory} to identify the presence of disease in a patient was estimated from the overlap of individual values across both samples.

**RESULTS**

Individual and mean data for metabolic, cardiovascular, ventilatory, and gas exchange variables are shown in Table 2. The VO2 increased in nine of ten patients during spontaneous breathing (Fig 2). The mean increase in VO2 was 38 ml (17 percent) (\( p < .05 \)). The breathing-related absolute and percentage increase in VO2 was not significantly different between the groups. The \( \Delta VO2 \) in group 1 was 27 ml/min (13 percent), and in group 2, patients with cardiorespiratory disease, it was 49 ml/min (20 percent). Patients in group 2 were larger, which explains the difference in absolute VO2 between the groups. When normalized by body surface area, mean VO2 values were similar in both groups.

All six patients with a Swan-Ganz catheter had an increase in \( Q \) during spontaneous breathing (Fig 3). The breathing-related increase was 1 L/min (16 percent).

**Table 2—Experimental Data for the Ten Study Patients**

<table>
<thead>
<tr>
<th>Case</th>
<th>MV</th>
<th>SB</th>
<th>MV</th>
<th>SB</th>
<th>MV</th>
<th>SB</th>
<th>MV</th>
<th>SB</th>
<th>J/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>1</td>
<td>223</td>
<td>283</td>
<td>8.49</td>
<td>10.05</td>
<td>7.64</td>
<td>6.99</td>
<td>29</td>
<td>40</td>
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<tr>
<td></td>
<td>2</td>
<td>238</td>
<td>245</td>
<td>6.83</td>
<td>7.52</td>
<td>7.25</td>
<td>7.79</td>
<td>37</td>
<td>37</td>
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<tr>
<td></td>
<td>3</td>
<td>218</td>
<td>241</td>
<td>6.74</td>
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<td></td>
<td>4</td>
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<td>6.91</td>
<td>7.79</td>
<td>5.92</td>
<td>30</td>
<td>38</td>
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<tr>
<td></td>
<td>5</td>
<td>208</td>
<td>213</td>
<td>6.02</td>
<td>7.20</td>
<td>8.97</td>
<td>5.23</td>
<td>26</td>
<td>40</td>
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<tr>
<td>Mean</td>
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<td>243</td>
<td>6.51</td>
<td>7.88</td>
<td>7.86</td>
<td>6.64</td>
<td>31.4</td>
<td>38.6</td>
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<tr>
<td>SD</td>
<td>20</td>
<td>25</td>
<td>1.02</td>
<td>1.25</td>
<td>.91</td>
<td>1.04</td>
<td>4.5</td>
<td>1.3</td>
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<td>Group 2</td>
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<td>306</td>
<td>336</td>
<td>8.28</td>
<td>5.65</td>
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<td>70</td>
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<td></td>
<td>2</td>
<td>236</td>
<td>250</td>
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<td>5.91</td>
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<td>321</td>
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<td>9.57</td>
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<td>25</td>
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<td>10.46</td>
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<td></td>
<td>5</td>
<td>247</td>
<td>286</td>
<td>6.57</td>
<td>11.26</td>
<td>7.66</td>
<td>26</td>
<td>40</td>
<td>17.24</td>
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<tr>
<td>Mean</td>
<td>256</td>
<td>305</td>
<td>9.71</td>
<td>7.78</td>
<td>31.4</td>
<td>44.6</td>
<td>11.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>31</td>
<td>36</td>
<td>1.52</td>
<td>2.05</td>
<td>7.3</td>
<td>16.4</td>
<td>4.63</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*MV, mechanical ventilation; SB, spontaneous breathing.

**FIGURE 2.** Mean, SD, and individual values of oxygen uptake (\( \dot{V}O_2 \)) during controlled mechanical ventilation (CMV) and spontaneous breathing (SB). Solid circles, values from group 1; open circles, values from group 2.

**Oxygen Uptake during Weaning (Hubmeyr et al)**

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This finding is consistent with the $\dot{V}O_2$ data and may reflect a cardiovascular adaptation to the increased metabolic demand. There was no consistent change in the arterial and mixed venous oxygen content difference. There was a significant but weak correlation between $\dot{V}O_2$ derived from the expired gas analysis and $\dot{V}O_2F$ calculated from the Fick equation (Fig 4).

The $\dot{V}E$ was lower during spontaneous breathing in all patients (Fig 5). The mean decrease of 1.6 L/min (18 percent) was associated with a significant increase in the PETCO$_2$ of 10 mm Hg (32 percent). The change in $\dot{V}E$ and alveolar ventilation is best explained by the need to hyperventilate patients mechanically to suppress spontaneous respiratory activity.

The relationship between WRESP and $\Delta \dot{V}O_2$ is shown in Figure 6. The WRESP was not significantly different between the groups (group 1, 9.38 ± 3.01 J/min; group 2, 11.99 ± 4.63 J/min). In addition, there was no correlation between the breathing-related change in $\dot{V}O_2$ and WRESP ($r = 0.2$). Neither measurement was predictive of weaning outcome.

**Discussion**

The main finding of this study is that the change in oxygen uptake with weaning and the measurement of respiratory work are inadequate predictors of successful weaning outcome in patients with respiratory failure. Although nine of the ten patients had an increase in $\dot{V}O_2$ during spontaneous breathing, this measure did not distinguish between patients with or without cardiopulmonary disease and ventilator-dependent respiratory failure. Although in carefully controlled experiments $\dot{V}O_2$ and force output of respiratory muscles are related, in this clinical setting $\Delta \dot{V}O_2$ was poorly correlated with WRESP.

It was clear from the outset that the transition from controlled mechanical ventilation to spontaneous breathing induces multiplex complex metabolic changes which affect $\dot{V}O_2$. The $\Delta \dot{V}O_2$ is not only determined by an increase in oxygen consumption of respiratory muscles ($\dot{V}O_{2 RESP}$), but is further augmented by weaning-related increases in stress hormone secretion, the recruitment of nonrespiratory muscles, and an increase in cardiac work. It can be argued that patients with large respiratory work and oxygen requirements also have a greater sympathetic discharge, are more likely to recruit nonrespiratory muscles when breathing spontaneously and demand a higher cardiac output. If this is true, $\Delta \dot{V}O_2$ should be highest in patients with severe heart-lung disease and correlate with estimates of respiratory work, even though $\Delta \dot{V}O_2$ may be quite different from $\dot{V}O_{2 RESP}$. The study did not substantiate these speculations.
Clinical Relevance

The clinical implications of our results are clear but disappointing. Although the populations from which our two samples were drawn might actually differ with regard to \( \Delta \dot{V}O_2 \) and \( W_{\text{RESP}} \), we cannot demonstrate that in our small sample. The analysis of five patients in each group suggest that at least 50 patients would need to be tested to evaluate group mean differences with any statistical confidence. This means that the combined true and random variability of work and \( \Delta \dot{V}O_2 \) is large enough to limit their predictive value and thus clinical usefulness as weaning parameters in individual patients. This is true for a host of other weaning values, which may be helpful in certain specific disease states but are not useful in most patients who require mechanical ventilation for prolonged periods. This lack of clinical promise caused us to abandon any further evaluation of the relationship between metabolic oxygen cost of weaning and the extent of cardiopulmonary impairment.

The magnitude of \( \Delta \dot{V}O_2 \) in this study is consistent with that in previous reports in the clinical literature. Thung et al.\(^6\) and Dammann\(^6\) first reported an increase in \( \dot{V}O_2 \) during the transition from mechanical to spontaneous ventilation in patients after open-heart operations. They measured oxygen uptake using a closed rebreathing system and reported an increase in \( \dot{V}O_2 \) between 2 percent and 41 percent. Wilson et al.\(^1\) using an open-circuit method similar to the one in this study, reported \( \Delta \dot{V}O_2 \) values ranging from 3.8 to 64.6 ml/m2/min in patients after mitral valve surgery. In their study, as in ours, minute ventilation was significantly lower during spontaneous breathing, and four of their patients had a respiratory exchange ratio exceeding 1 during mechanical ventilation, suggesting that nonsteady-state conditions may have limited the accuracy of their results. Field et al.\(^4\) described 13 medical patients, most of whom had chronic obstructive pulmonary disease. In their study, the mean \( \Delta \dot{V}O_2 \) was also 24 percent, and it exceeded 100 percent in one patient. Bursztein et al.\(^1\) studied 20 young patients with trauma, including burns and postoperative sepsis. These patients had no obvious impairments in pulmonary function and were breathing room air, yet their \( \Delta \dot{V}O_2 \) was also 24 percent, exceeding 30 percent in four patients. In many of these studies, it was assumed that \( \Delta \dot{V}O_2 \) was primarily determined by the oxygen uptake of respiratory muscles, although no independent measurement of their energy requirements was made.

The similarity of \( \Delta \dot{V}O_2 \) values of different patient populations, with little to severe impairment in cardiopulmonary function, is consistent with our observations and provides indirect evidence that \( \Delta \dot{V}O_2 \), as measured in these studies and our own study, may not primarily reflect the energy requirements of respiratory muscles.

We will now discuss the technical limitations of indirect calorimetry in this patient population, explore the evidence about why factors other than \( \dot{V}O_{\text{RESP}} \) must have significantly affected \( \Delta \dot{V}O_2 \), and describe the limitations of \( W_{\text{RESP}} \) as a measure of the integrated force output of respiratory muscles in our patients.

Technical Limitations of \( \Delta \dot{V}O_2 \) Measurements

In patients breathing oxygen-enriched gas mixtures, the determination of \( \Delta \dot{V}O_2 \) by gas collection methods becomes critically dependent on the accuracy of the oxygen-measuring device.\(^2\) We took great care to avoid oxygen analyzer drift and are confident that systematic errors in our \( \dot{V}O_2 \) measurements were small. It is also crucial that these measurements be made under steady-state conditions.\(^3\) Although four of the five patients in group 2 ultimately required reinstitution of mechanical ventilation on the day they were studied (patients 6, 8, 9, and 10), all achieved
steady-state gas exchange after 20 minutes of spontaneous breathing. Data from four additional patients were excluded from this report, because they became tachypneic immediately after cessation of mechanical ventilation, and their oxygen uptake progressively decreased. This occurred because \( V_{E} \) fell sharply, and there was a continuous build-up in body stores of CO2. Under these non–steady-state conditions, the much lower \( V_{E} \) dominates the calculation of VO2.

We compared VO2, measured at the mouth, with that derived from the Fick equation (\( V_{O2,F} \)). Although there was no significant difference between measurements, their correlation was relatively weak (Fig 4). This finding is largely explained by the variability of cardiac output measurements with the thermodilution technique in a clinical setting.\(^{24}\) For example, as soon as a technician manipulated the Swan-Ganz catheter to make an output measurement, VO2 measured at the mouth increased by approximately 5 percent. Furthermore, in laboratory animals with lung disease, the Fick method can underestimate VO2 measured at the mouth\(^{25}\) because bronchial and thebesian veins empty into the systemic circulation and the oxygen consumed by parts of the lung and heart is not reflected in the Fick measurement. We believe that VO2 derived from cardiac output and mixed venous and arterial oxygen content determinations is less accurate than that derived from expired gas collection methods, primarily because of problems with the thermodilution technique. The \( V_{O2,F} \) as derived from \( Q \) was measured at six points in time, whereas gas collection measurements were averaged over five minutes.

**Contribution of Factors other than \( V_{O2,RES} \) to \( \Delta VO2 \)**

To interpret breathing-related changes in oxygen uptake as a measure of oxygen consumed by the respiratory muscles, one must assume that the oxygen metabolism of tissues other than the respiratory muscles remains constant. However, stress hormone secretion, the recruitment of nonrespiratory muscles, cardiac work and factors related to an altered acid base homeostasis must be considered. In normal humans, the infusion of stress hormones increases VO2 by 20 percent, a value similar in magnitude to the \( \Delta VO2 \) values we observed in this study.\(^{26}\) While many patients, particularly those with cardiorespiratory disease, recruited shoulder girdle muscles to stabilize and/or move the chest wall, it can be argued that this action is related to breathing. None of our patients had flailing arm or leg motion, and all seemed sufficiently comfortable to achieve a steady state as defined by the constancy of the metabolic and ventilatory measurements and the range of \( R \) values. The amount of oxygen consumed by the heart in the response to an increase in cardiac work is variable and cannot be reliably estimated from cardiac output and blood pressure measurements alone.\(^{28}\) While these variables probably augmented \( \Delta VO2 \) relative to \( VO2,RES \) in our patients, their effect may have been offset in part by the influence of a weaning-related fall in alveolar ventilation.

Effects of pH and the arterial carbon dioxide tension (PaCO2) on oxygen uptake have previously been studied in laboratory animals\(^{27}\) and humans.\(^{28}\) In humans, Karetzky and Cain\(^{28}\) found a substantial decrease in VO2 when subject inhaled CO2 while keeping the breathing pattern and \( V_{E} \) constant. The mechanism by which pH and PaCO2 effect the oxygen metabolism of tissues has not been elucidated, but they may be related to the pH dependence of enzymes involved in aerobic metabolism. A weaning-related fall in alveolar ventilation was observed in all patients and may have reduced \( \Delta VO2 \).

**Limitation of \( W_{RES} \) as Measure of Respiratory Muscle Force Output**

In a well-controlled experimental setting, with careful attention to breathing patterns and isocapnic conditions, \( \Delta VO2 \) is a reasonable estimator of the oxygen consumed by respiratory muscles. This is supported in the studies by Field et al,\(^{7}\) who showed that in normal volunteers during inspiratory resistive loading, the transdiaphragmatic pressure time index, which should reflect diaphragmatic energy requirements and blood flow,\(^{29}\) correlated well with \( \Delta VO2 \). Work performed on the lung was also related to \( \Delta VO2 \), although the correlation was weaker. This is in contrast to our findings in patients, and we will now explore the reasons for this discrepancy.

The determinants of respiratory muscle energy needs are a complex function of tension, contraction and relaxation time, and the velocity of fiber shortening.\(^{30}\) The measurement of respiratory power is an attempt to quantify the forces exerted by the respiratory muscles on the respiratory system, which in theory should correlate with their energy needs. To measure respiratory power on lung and chest wall, one must assume that the forces exerted on the respiratory system during a mechanical inflation are equal to the force output of the respiratory muscles during a spontaneous breath with an identical tidal volume and flow pattern,\(^{31}\) that is, the mechanical efficiency with which a ventilator inflates the respiratory system is assumed equal to the mechanical efficiency of the inspiratory muscles. Several observations argue strongly against the validity of this assumption.

In patients with respiratory system diseases, the deformation of the chest wall during mechanical ventilation and spontaneous breathing is different.\(^{32}\) Muscles that stabilize or distort the chest wall consume
energy, but their action is not directly reflected in respiratory work measurements. Indirect evidence suggesting that these factors are important even in normal humans was reported by Baydur et al., who described large differences in the passive and effective impedance of the respiratory system. Therefore, the large discrepancies in the relationship between work and \( \dot{V}O_2 \) reported in the literature have been explained with differences in the mechanical efficiency with which inspiratory muscles act on the respiratory system in various disease states.\(^{1,13,14,16,34}\)

Interpreting our data in this light, one would conclude that the efficiency (\( \text{ERESP} \)), defined as the ratio of inspiratory work and the work equivalent of \( \Delta \dot{V}O_2 \), ranged from 0.47 percent to 5.56 percent. In one patient, in whom \( \Delta \dot{V}O_2 \) decreased with spontaneous breathing, this calculation could not be made. In our study, the hypothetical values of \( \text{ERESP} \) were not significantly different in patients without (2.27 percent) and those with (1.7 percent) heart-lung disease. Although these values are similar to those reported for patients with chronic obstructive pulmonary disease,\(^{1,13,14,16,34}\) for several reasons we cannot accept them as valid.

The mechanical efficiency of respiratory muscles in patients with respiratory system disease, particularly emphysema, is much smaller than that in normal controls. We would therefore have expected \( \text{ERESP} \) to be lower in group 2 than group 1. Further, it is unreasonable to assume that the mechanical efficiency of respiratory muscles is <1 percent, when \( \text{in vitro} \) measurements have shown that skeletal muscles contracting under isotonic conditions have efficiencies (ratio of external work and heat production) of 25 percent or more.\(^{35}\) We realize that tidal volume, breathing frequency, and inspiratory flow pattern during mechanical ventilation affect the measurement of work even when normalized by minute ventilation, as done in this study. In this study, the breathing patterns during spontaneous breathing could not be controlled. However, we do not think that these factors by themselves are sufficient to explain the lack of correlation between \( \Delta \dot{V}O_2 \) and \( \text{ERESP} \) and the range of calculated efficiencies in this study.

In our experimental setting, neither \( \Delta \dot{V}O_2 \) nor \( \text{WRESP} \) are adequate measures of the combined force output of the inspiratory muscles. Even if they were, the inspiratory force necessary to sustain adequate ventilation cannot be the only factor responsible for respiratory failure. Muscle endurance and oxygen delivery to the respiratory muscles may also play a key role in the pathophysiology of this syndrome.\(^{36}\) If muscle perfusion were inadequate, respiratory muscle oxygen consumption would be limited, which would decrease the apparent oxygen cost of breathing. None of our patients was in shock, so that a delivery limitation of total body oxygen consumption seems unlikely.\(^{37}\) However, we cannot exclude that the oxygen delivery to the respiratory muscles, particularly in group 2 patients, was inadequate to meet the metabolic demand.

We confirmed previous observations indicating that \( \Delta \dot{V}O_2 \) during the transition from mechanical ventilation to spontaneous breathing is approximately 20 percent. The large variability in \( \Delta \dot{V}O_2 \) and \( \text{WRESP} \) within and across our experimental groups limits their usefulness in the evaluation of disease state and weaning decisions in individual patients. Further, we do not believe that \( \Delta \dot{V}O_2 \) is an adequate measure of the combined force output and energy requirements of respiratory muscles when breathing pattern, alveolar ventilation, and stress hormone response cannot be controlled.

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REFERENCES

50th Anniversary, Mexican Society of Pulmonary and Thoracic Surgery

The Mexican Society of Pulmonology and Thoracic Surgery will celebrate its 50th year March 6-11 in Mexico City. The meeting will include postgraduate courses, honor lectures, major symposia and original investigations. Simultaneous translation will be provided. For information and abstract forms, contact Dr. Carlos Ibarra-Perez, FCCP, President, Sociedad Mexicana de Neumología y Cirugía de Torax, Retorno De Los Leones 58, Mexico City CP 01710, Mexico.