Energy Expenditure Associated with CPAP and T-Piece Spontaneous Ventilatory Trials

Changes Following Prolonged Mechanical Ventilation


The use of portable metabolic carts to assess energy expenditure (EE) by measuring oxygen consumption (Vo,) and carbon dioxide production (Vco,) has recently been applied to patients undergoing weaning from mechanical ventilation. The Vo, and EE can be used to estimate changes in the work of breathing (WOB) associated with different weaning strategies. The purpose of this study was to use Vo, and EE to assess changes in the WOB when assisted mechanical ventilation (AMV) was replaced with two spontaneous ventilatory trial (SVT) techniques: continuous positive airway pressure (CPAP) and T-piece. Nine difficult-to-wean patients were studied during the initial weaning period following 26 ± 18 days (mean ± SD) of mechanical ventilatory support. The Vo, and EE during all AMV were 296 ± 75 ml/min and 2069 ± 519 kcal/day, respectively. Compared to the baseline AMV levels, during CPAP overall Vo, and EE increased 14 percent and 13 percent, respectively, and during T-piece overall Vo, and EE increased 20 percent and 19 percent, respectively. Respiration rate (f) increased and tidal volume (VT) decreased during both SVTs compared to AMV although no significant change in minute ventilation was seen. The WOB, as judged from changes in Vo, was only 5 percent higher during T-piece compared to CPAP; however, patients tolerated an average of only 141 ± 45 min on T-piece vs 165 ± 29 minutes on CPAP. We conclude that during the initial weaning stages in patients who have received prolonged mechanical ventilatory support, the WOB associated with SVTs is increased compared to AMV but that the WOB associated with T-piece is not significantly greater than that for CPAP. (Chest 1989; 96:867-72)

EE = energy expenditure; AMV = assisted mechanical ventilation; SVT = spontaneous ventilatory trial

Certain groups of mechanically ventilated, critically ill patients are difficult to wean from prolonged ventilation despite advanced respiratory support technology and sophisticated monitoring techniques. The art of weaning these patients is based on clinical assessment by the physician using commonly accepted criteria. Several techniques are currently employed to facilitate weaning, including intermittent mandatory ventilation (IMV) and spontaneous ventilatory trials (SVT). Controversy exists regarding the "best" approach to weaning, and there is little scientific information upon which to choose a preferred technique.

Weaning is often initiated with IMV trials. As the patient tolerates decreasing rates of IMV, a series of SVTs are commonly introduced to evaluate the patient's ability to sustain prolonged spontaneous ventilation and to provide increasing training periods to exercise respiratory muscles. For SVTs, physicians can choose one of several different methods, such as CPAP delivered through the ventilatory system; an external CPAP system in which high flow gases are delivered to the patient independent of the ventilator; or an external T-piece system which provides the patient with continuous high flow gases without CPAP.

Changing from ventilator-assisted respiration to spontaneous ventilation requires the use of the respiratory muscles and is associated with increased Vo, and EE. Measurements of Vo, and EE have been used as indices of changes in the WOB. The purposes of this study were as follows: (1) measure Vo, and EE to assess changes in the WOB associated with SVTs in patients who have received prolonged ventilatory support; and (2) compare the WOB required by two commonly used weaning methods, high flow external circuit CPAP and T-piece.

**Materials and Methods**

Nine mechanically ventilated patients (six men, three women) admitted to the General Systems Intensive Care Unit (ICU) at the University of Alberta Hospital were studied. The protocol was approved by the Ethics Committee of the University of Alberta, and informed consent was obtained for all participants. All patients were intubated secondary to respiratory failure and received prolonged AMV. On admission to ICU, the APACHE II scoring system was used to assess the patients' severity of illness. Patients' clinical descriptions, admission APACHE II scores, ventilatory parameters prior to weaning, and the number of days of previous ventilatory support are presented in Table 1.

Oxygen consumption, Vco, and EE were determined using an open circuit indirect calorimetry system. Energy expenditure was calculated from measured Vo, and Vco, using the relationship

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Table 1—Patient Characteristics*

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age/Sex</th>
<th>Clinical Description</th>
<th>Admission APACE II Score</th>
<th>Ventilatory Parameters (Day Prior to Wean)</th>
<th>Days of Previous Ventilatory Support</th>
<th>Duration of Weaning Attempt, Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62 M</td>
<td>Coronary artery bypass graft, COPD, ARDS, hypertension</td>
<td>20</td>
<td>800</td>
<td>300</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>36 M</td>
<td>MVA—fractured pelvis, ARDS, sepsis, acute renal failure</td>
<td>17</td>
<td>600</td>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>77 F</td>
<td>MVA—fractured ribs and ankle, aspiration pneumonia</td>
<td>15</td>
<td>800</td>
<td>300</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>86 F</td>
<td>COPD, respiratory arrest, malnutrition</td>
<td>24</td>
<td>200</td>
<td>150</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>59 F</td>
<td>Asthma, perforated sigmoid diverticulitis, Pseudomonas pneumonia, septicemia</td>
<td>13</td>
<td>600</td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>17 M</td>
<td>MVA—flail sternum, pulmonary contusion, pneumothoraces</td>
<td>8</td>
<td>900</td>
<td>400</td>
<td>35</td>
</tr>
<tr>
<td>7</td>
<td>59 M</td>
<td>Staphylococcal endocarditis, brain abscess, acute renal failure, aortic valve replacement</td>
<td>16</td>
<td>650</td>
<td>400</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>65 M</td>
<td>Fractured T10, multiple rib fractures, ARDS, pneumonia</td>
<td>7</td>
<td>1100</td>
<td>800</td>
<td>30</td>
</tr>
<tr>
<td>9</td>
<td>29 M</td>
<td>Diesel fuel aspiration, ARDS, pneumonia</td>
<td>13</td>
<td>2000</td>
<td>650</td>
<td>50</td>
</tr>
</tbody>
</table>

Mean ± SD: 15 ± 5, 850 ± 500, 410 ± 200, 31 ± 11, 26 ± 18, 21 ± 7

*COPD, chronic obstructive pulmonary disease; ARDS, adult respiratory distress syndrome; MVA, motor vehicle accident.
†Patient died.

derived by deV Weir* using Kleiber's tables* and is expressed by the following equation:

\[
\text{EE} = \left(3.796 \times \text{VO}_2 + 1.214 \times \text{VCO}_2\right) 1.44^* \\
\text{(kcal/day)} = \left(\text{mL/min} \times \text{min/L} \times 1400 \text{min/day}\right) / 1000 \text{ ml}
\]

The system used has been previously validated at this institution* for accuracy in VO₂ and VCO₂ at various fractions of inspired oxygen (FIO₂), breathing frequencies (f) and Vr. The accuracy in VO₂ at FIO₂ levels of 0.22 and 0.40 were 2.6 ± 0.3 percent and 3.5 ± 0.4 percent, respectively. In this study, no patient received an FIO₂ greater than 0.35. The error in VCO₂ measurements at all FIO₂ levels tested was 2.6 ± 0.4 percent. Although FIO₂ was measured every 30 s, an external air-oxygen blender was used to minimize fluctuations in FIO₂.

The decision to begin weaning a patient from AMV was based on clinical assessment by the attending physician using standard objective and subjective weaning criteria. As an additional assessment of weaning capability, all patients entered into the study underwent a 20-minute trial of spontaneous ventilation to ensure that this minimum amount of spontaneous ventilation could be achieved without the patient exhibiting signs of fatigue. The fatigue criteria used are presented in Table 2. All patients in this study successfully completed the 20-minute trial. Following the trial wean, patients were rested overnight (minimum 8 h) on AMV.

The study was conducted on two consecutive days (Fig 1). On day 1, an initial resting EE measurement was made for a 30-minute period while the patient rested quietly on AMV. The patient was then randomly assigned to a weaning mode, either a high flow external circuit CPAP with +5 cm H₂O pressure or a high flow T-piece system. The patient was maintained on the SVT for a maximum of 180 minutes or until signs of fatigue were exhibited (Table 2). The VO₂ and EE were measured continuously during the SVT. Heart rate and blood pressure were recorded every five to ten minutes during the weaning study using a radial artery catheter.

In six of the nine patients, arterial blood was taken toward the end of the particular ventilation mode for analysis of FIO₂ and PaCO₂ (Table 3). The PaCO₂ was divided by PaO₂ to compare oxygenation with the three modes of ventilation and to minimize the effects of changes in FIO₂. The PaO₂ was calculated using the alveolar air equation with values for FIO₂ and respiratory exchange ratio (R) obtained from the metabolic cart.

Once fatigue occurred or the 180-minute maximum for the SVT was achieved, the patient was then rested on AMV for a minimum of 90 minutes. During the last 30 minutes of the rest period, VO₂ and EE were measured to determine the baseline values for the second weaning mode. Following this rest period, the patient was placed on the alternate SVT. Again, VO₂ and EE were measured continuously for a maximum of 180 minutes or until the fatigue criteria were met. All other measurements were performed as outlined above.

The second SVT period completed day 1 of the study and the patient was rested overnight on AMV. On day 2, the measurements were performed in an identical fashion except the order of the SVT was reversed (Fig 1). During the two-day study period, the patient's

Table 2—Factors Used to Determine Fatigue in Patients During Spontaneous Ventilation

Subjective:—nasal alar flaring
—patient distress
—indrawing
—sweating, agitation
—use of accessory muscles of respiration
—uncoordinated ventilation

Objective:—f increased greater than twice baseline
—HR increased greater than 30% baseline
—BP increased to greater than 20% baseline systolic

Energy Expenditure with CPAP and T-Piece (Swimmer et al)
Table 3—Blood Gas Results*

<table>
<thead>
<tr>
<th></th>
<th>AMV</th>
<th>TP</th>
<th>AMV</th>
<th>CPAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>PaO2/PO2</td>
<td>0.52 ± 0.06</td>
<td>0.50 ± 0.12</td>
<td>0.50 ± 0.10</td>
<td>0.48 ± 0.11</td>
</tr>
<tr>
<td>PaCO2</td>
<td>37.1 ± 11.0</td>
<td>38.8 ± 9.9</td>
<td>36.7 ± 5.5</td>
<td>41.6 ± 9.6</td>
</tr>
</tbody>
</table>

*Values expressed as mean ± SD.

Values of p < 0.05 compared to previous AMV value.

To minimize bias of performing SVT during morning vs afternoon, the average VO2 and EE for each of the two CPAP and T-piece SVTs for each patient were computed, and in assessing patterns of VO2 and EE during the SVTs, data for each 15-minute time interval were averaged. Values of percentage change from the preceding AMV (rest) period were calculated using the following equation:

% change = \( \frac{\text{SVT} - \text{AMV}}{\text{AMV}} \) × 100%

All comparisons of AMV vs SVTs and comparisons of CPAP vs T-piece were done using Student’s paired t test. A p value ≤ 0.05 was considered statistically significant.

RESULTS

The age of the patients studied was 54 ± 23 years and the APACHE II score on admission to ICU was 15 ± 5 (Table 1). Two of the patients had previously documented underlying lung disease (patients 1 and 4) and the remaining seven patients had developed severe respiratory failure (ARDS) secondary to trauma or sepsis. In all cases, patients received prolonged mechanical ventilatory support (26 ± 18 days) before commencement of the weaning study. The weaning studies were done at the beginning of the weaning period and, on the average, a period of 21 ± 7 days of additional weaning (excluding patient 4 who was ventilator dependent for >1 year and patient 3 who died before weaning was successful) was required before complete spontaneous respiration was achieved.

Four patients (patients 1, 2, 8, and 9) tolerated the 180-minute SVT for CPAP and T-piece on both study days. These patients were successfully weaned in 18 ± 6 days following the study. Four patients (patients 3, 5, 6, and 7) were unable to tolerate 180 minutes of CPAP and T-piece and could not be successfully weaned until 38 ± 32 days following the study. Patient 4 remains ventilator dependent and therefore was excluded from this comparison. The average amount of time all patients tolerated T-piece during the study was 141 ± 45 minutes vs 165 ± 29 minutes for CPAP (p < 0.05). Patients 3 and 6 tolerated 180 minutes of CPAP on both study days but were fatigued on T-piece after 155 ± 5 minutes and 102 ± 70 minutes, respectively. There was no correlation between the number of days required to wean the patient following the weaning study and the degree to which VO2 and EE exceeded the AMV levels.

The average mean value for VO2, EE, and f increased significantly during the SVTs compared to AMV (p < 0.01, Fig 2). The VO2 and EE increased from 293 ± 78 ml/min and 2086 ± 519 kcal/day, respectively, during AMV to 355 ± 91 ml/min and 2457 ± 632 kcal/day during T-piece. This corresponds to a 20 percent increase in VO2 and a 19 percent increase in EE during T-piece. The VO2 and EE increased from 293 ± 78 ml/min and 2052 ± 514 kcal/day, respectively, on AMV to 337 ± 78 ml/min and 2330 ± 536 kcal/day on CPAP. This corresponds to a 14 percent increase in VO2 and a 13 percent increase in EE during CPAP. The VO2 and EE were higher (but not significantly) during T-piece compared to CPAP. However, in 13 of the 18 weaning trials (ie, two per patient), T-piece was associated with an increased VO2 and EE (Fig 3). The respiratory exchange ratio did not change significantly between any of the modes of ventilation, so the percentage changes in VCO2 were similar to those seen for VO2. Six patients tolerated the 180-minute study period on CPAP, whereas four patients achieved the 180 minutes on T-piece.

Respiration rate while on AMV was 20 ± 6 breaths/minute. During the SVTs, f increased to 38 ± 11
breaths/min on T-piece and 36 ± 11 breaths/min on CPAP (p<0.01). This corresponds to a 92 ± 47 percent increase on T-piece and a 86 ± 46 percent increase on CPAP above the AMV measurements. Tidal volume was lower during both T-piece (0.308 ± 0.095 L) and CPAP (0.306 ± 0.073 L) compared to AMV (0.631 ± 0.169 L).

Although there were no significant changes in \( \dot{V}E \) between AMV and T-piece or CPAP, PaCO\(_2\) increased significantly during CPAP compared to the previous AMV value suggesting a slightly larger decrease in alveolar ventilation occurred during CPAP than during

![Figure 2](image)

**Figure 2.** Changes in \( \dot{V}O_2 \), EE, f, \( V_T \), and \( \dot{V}E \) during T-piece and CPAP weaning trials compared to the preceding values for AMV. Values expressed as mean ± SD. Differences between AMV and T-piece or CPAP are indicated by asterisk (p<0.05). There were no significant differences between T-piece and CPAP.

T-piece (Table 3). All patients had low values for PaO\(_2\)/PaO\(_2\) (Table 3), but the SVTs did not cause a significant change.

**Discussion**

In the last two decades, there have been a number of studies of different techniques used to wean patients from mechanical ventilation.\(^6^1\) Traditionally, measurements of \( \dot{V}O_2 \) and EE have been made using short-term collection of expired gases\(^7\) or by thermodilution measurements of cardiac output and arterial-venous \( \dot{O}2 \) difference.\(^1\) These methods permit only instantaneous measurement of gas exchange, which can fluctuate considerably from time to time during the weaning process. Therefore, one must question the validity of statements about EE when only one or a few spot measurements are made during weaning since infrequent measurements may not reflect the overall EE required during a weaning trial.

More recently, portable metabolic carts have been used to continuously assess the weaning process.\(^8\)\(^1\) Lewis et al\(^8\) studied a group of mechanically ventilated patients to evaluate the oxygen cost of breathing associated with AMV compared to spontaneous breathing using IMV. They found that patients who were successfully weaned within 24 h showed only an 8 percent increase in \( \dot{V}O_2 \) compared to a 25 percent increase in \( \dot{V}O_2 \) in patients who could not be success-
fully weaned in 24 h. In contrast to their results, we did not find a correlation between the percent increase in \( \text{V} \text{O}_2 \) during the SVTs compared to AMV and the number of days it took for successful weaning to occur. These differing results may be explained by the fact that different patient populations were studied. All the patients in our study had been mechanically ventilated for at least ten days prior to any weaning attempt and required a minimum of ten days of weaning before successful extubation.

In normal individuals, the work of breathing is only 4 percent or less of the total \( \text{V} \text{O}_2 \). In our group of critically ill patients who required prolonged ventilatory support, \( \text{V} \text{O}_2 \) increased 20 percent during T-piece and 14 percent during CPAP over AMV levels. Several factors may have contributed to the increased \( \text{V} \text{O}_2 \) in these patients including: uncoordinated breathing; stiff lungs; high airway resistance, and muscle wasting secondary to reduced nutritional intake or hypercatabolism.

In the five patients who did not complete the 180-minute SVTs, CPAP was tolerated longer. The reason for this is likely that CPAP does a portion of the work to overcome the elastic recoil of the lung, thus causing decreased elastic work of inspiration. The elastic recoil of the lung does the work required for expiration as long as the airway resistance is not too high. The CPAP may even decrease the work of breathing in patients who have airway obstruction by increasing the functional residual capacity, decreasing airway resistance, and providing greater elastic recoil to aid expiration. One might also postulate that the force-length relationship of the chest wall musculature may improve with the increased functional residual capacity, maximizing efficiency and thereby decreasing oxygen requirements. In addition to these theoretical advantages, Venus et al. have shown 5-cm \( \text{H}_2\text{O} \) CPAP did not cause any detrimental cardiovascular effects. In spite of the theoretical benefits of CPAP on decreasing the work of breathing, there was not a statistically significant difference in \( \text{V} \text{O}_2 \) and EE between CPAP and T-piece in our study, although the significant prolongation of SVT time on CPAP compared to T-piece suggests some supportive benefit from CPAP.

We conclude that both CPAP and T-piece are associated with a significant increase in work of breathing in critically ill patients who have been on prolonged mechanical ventilation. During the initial stages of weaning, T-piece is associated with a higher \( \text{V} \text{O}_2 \) and EE compared to CPAP and in many cases, the patient was unable to maintain as long a SVT on T-piece compared to CPAP. A clinical implication of our findings is that CPAP weaning during the early weaning stages may be preferred to T-piece because of the patients' ability to remain on the CPAP system longer, thus providing greater opportunity to reestablish coordinated breathing while at the same time exercising the respiratory muscles to nearly the same degree as with T-piece weaning. Our data, however, cannot provide an answer as to whether CPAP is associated with a shorter weaning period compared to T-piece.

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