A Predictive Equation for Determination of Resting Energy Expenditure in Mechanically Ventilated Patients*

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Study objective: To evaluate an equation that estimates resting energy expenditure from two easily obtained measurements—expired carbon dioxide and minute ventilation, and compare the results of this equation with standard methods of estimating and measuring caloric expenditure in mechanically ventilated patients.

Design: Prospective evaluation in a consecutive, unselected cohort.

Setting: Medical, surgical, and coronary intensive care units in a university hospital.

Patients: Twenty-five patients (16 to 79 years of age) receiving mechanical ventilation.

Intervention: Indirect calorimetry (IC), minute ventilation (Ve), and partial pressure of expired carbon dioxide (PeCO2) were obtained on all patients. Harris-Benedict equations were calculated and corrected for known stress factors (HBc). Calculated energy expenditure (CEE) was determined using the following equation:

CEE = 9.27 × Ve × PeCO2

CEE was then compared with IC and HBc.

Measurements and results: The IC was interpretable in 22 of 25 patients, and CEE was significantly better at estimating caloric requirements than HBc. The mean absolute difference between CEE and IC was significantly less than between HBc and IC (118 ± 96 vs 302 ± 269, p < .003). CEE estimated caloric requirements to within 200 kcal of IC in 16 of 22 (72 percent); HBc estimated within 200 kcal of IC in 9 of 22 (41 percent).

Conclusions: Minute ventilation and expired carbon dioxide measurements are easily and inexpensively obtainable. Energy expenditures calculated from these measurements (CEE) compare favorably with values obtained from a metabolic cart and are significantly more accurate than HBc.

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Multiple physiologic stresses in critically ill patients can complicate prescriptions for nutritional support. Though calculations are available to estimate these metabolic demands, it has been shown previously that equations used for predicting resting energy expenditure (REE) do not accurately assess the caloric requirements of critically ill patients.1,4 Inaccurate nutritional assessment may lead to adverse effects from either underfeeding or overfeeding. Malnutrition, for example, delays wound healing, decreases resistance to infection, and may increase postsurgical complications.1 Conversely, overfeeding can cause hyperventilation, hepatic steatosis, and dysfunction, as well as elevated plasma triglyceride and cholesterol levels.5

Although the principles of indirect calorimetry have been well established for many years, the calculation of caloric requirements was facilitated by Weir,7 who described a convenient equation that related caloric needs to oxygen consumption (VO2) and carbon dioxide production (VCO2). Recent advances in technology have led to fully automated metabolic carts that can indirectly measure energy expenditure expeditiously. However, the cost of a metabolic cart is high and the availability is consequently limited. Furthermore, the use of a metabolic cart requires technical personnel familiar with its operation as well as significant technician time to perform the procedure. The use of indirect calorimetry is thus limited to those hospitals willing to pay for the equipment and technical time.

Because these expenditures may be prohibitive in many centers, a formula was derived from one of Weir's original equations to estimate a calculated resting energy expenditure (CEE) from two easily obtainable measurements—expired partial pressure of carbon dioxide (PeCO2) and expired minute ventilation (Ve). The purpose of this study was to see whether this new, simple method of calculating energy expenditure from expired gas sampling approximated actual caloric requirements better than using the standard anthropometric calculations of Harris and Benedict.

METHOD

Derivation of Equations

Weir's equation relating caloric consumption to gas exchange states that

\[ (1) \ K = 3.9 + 1.1R \]
where $K$ is the caloric value of 1 L of oxygen in kg cal and $R$ is the respiratory quotient. Weir multiplied both sides of this equation by liters of oxygen consumed to obtain the familiar equation

$$(2) \quad V_{O2} \times K = (3.9 \times V_{O2}) + (1.1 \times V_{CO2})$$

or

$$(3) \quad EE = (3.9 \times V_{O2}) + (1.1 \times V_{CO2})$$

where $EE$ is energy expenditure in kilocalories per day, and $V_{O2}$ and $V_{CO2}$ are consumption and production of gas in liters per day, and the patient is in steady state. If, instead, we assume an $R$ of 0.93 in equation 1, reflecting mixed substrate utilization, then

$$(4) \quad K = 3.9 + (1.1 \times 0.93)$$

$= 4.813$ kg cal per liter oxygen consumed

Since $R = V_{CO2}/V_{O2}$

$$(5) \quad K/R = kg \text{ cal per liter of carbon dioxide produced}$$

$$(6) \quad 4.813 \times \frac{K}{R} = 5.799$ kg cal per liter of carbon dioxide produced therefore

$$(7) \quad CEE = 5.799 \times V_{CO2}$$

where $CEE$ is "calculated" energy expenditure in kilocalories per day and $V_{CO2}$ is carbon dioxide produced in liters per day.

We can approximate $V_{CO2}$ by measuring minute production of carbon dioxide ($V_{CO2}$) and extrapolate over 24 h.

$$(8) \quad CEE = (5.799 \times V_{CO2}) \times 1.440 \text{ min/day} \times 1 \text{ L/1,000 ml}$$

$$(9) \quad CEE = 8.350 \times V_{CO2}$$

Substituting $V_{CO2} = (Ve \times PaCO2)/0.901$

$$(10) \quad CEE = 9.27 \times Ve \times PaCO2$$

where $Ve$ is minute ventilation in liters per minute and $PaCO2$ is the partial pressure of mixed expired carbon dioxide in mm Hg (see appendix). The factor of 0.901 corrects for the expression of $V_{CO2}$ as dry gas volume production at standard temperature and pressure (STPD), whereas $Ve$ and $PaCO2$ are saturated and measured at ambient temperature and pressure (ATPS).

The equation can also be derived from equation 3 by substituting $V_{CO2}/R$ for $V_{O2}$.

**Protocol**

Indirect calorimetry (IC) was performed on 25 patients receiving mechanical ventilation. Patients were excluded if they were medically unstable, agitated, or uncooperative. To avoid $V_{O2}$ measurement errors seen with high levels of inspired oxygen, patients were excluded if their fraction of inspired oxygen was greater than 50 percent.

Basal energy expenditure was predicted using the Harris-Benedict equations:

male: $BEE = 66 + 13.7W + 5H - 6.8A$

female: $BEE = 655 + 9.7W + 1.8H - 4.7A$

where $W$ is the patient's weight in kilograms, $H$ is the height in centimeters, and $A$ is the age in years.

Basal energy expenditure calculated from the Harris-Benedict equation was then corrected for stress factors (corrected Harris-Benedict equation—HBc) using previously published guidelines. These stress factors and caloric requirements were calculated independently by nutritionists and confirmed by physicians caring for the patients who were not otherwise involved in the study.

Minute oxygen consumption ($V_{O2}$) and CO$_2$ production ($V_{CO2}$) were measured using a metabolic cart (Sensormedics Deltrac, Sensormedics, Yorba Linda, Calif). Volume and two-point gas calibration of the metabolic cart was performed at the beginning of each study. The system was checked for leaks prior to each test. Oxygen blenders (Bird Products Corp, Palm Springs, Calif) were used to reduce fluctuations in Fio$_2$ during the test. Indirect calorimetry testing was considered acceptable if the measured R was in the physiologic range (0.67 to 1.3) and if steady-state measurements were obtained. Steady state was defined by less than 10 percent change in $V_{O2}$ and $V_{CO2}$ and less than 5 percent change in average R over a 5-min interval per criteria of Makk et al. Resting energy expenditure was calculated from $V_{O2}$ and $V_{CO2}$ using the equation of Weir:

Immediately following indirect calorimetry, $Ve$ was measured using a calibrated mechanical spirometer (Boehringer, model 8800, Boehringer Laboratories, Indianapolis, Ind). Three 1-min measurements were obtained and averaged. The PrCO$_2$ was measured by collecting 5 L of expired gas in a neoprene balloon, withdrawing 10 ml of mixed gas and analyzing the expired gas in a blood gas system (Ciba-Corning 290). Calculated energy expenditure based on expired CO$_2$ and minute ventilation (CEE) was then calculated using equation 10 (above).

This protocol was approved by the Institutional Review Board prior to initiating the study.

**Statistical Analysis**

Data are presented as mean ± standard deviation (SD), except for slopes and intercepts for correlation data, which are presented as standard error. To assess variability of both methods (HBc and CEE) compared with indirect calorimetry, 95 percent confidence intervals were constructed using the method of Bland and Altman. For illustrative purposes, scatterplots were produced comparing the results of the new predictive equation and HBc to the results obtained by indirect calorimetry. The degree of linearity was assessed by Pearson’s r coefficient. Where applicable, differences between variables were assessed by Student’s t test for paired variables.

**Results**

A total of 25 metabolic studies were performed. Three patients had uninterpretable studies—two did not meet steady-state criteria, and one had an R value dramatically from...
provides a reasonable estimate in 9 (41 percent). The CEE overestimates caloric needs in 5 patients (23 percent), underestimates the requirements in 1 (5 percent), and provides a reasonable estimate in 16 (72 percent) (Fig 1).

The VCO₂ measured by collection of expired gas correlated with the VCO₂ measured by the metabolic cart (Fig 2, r = 0.94, slope = 0.97 ± 0.08, intercept = 19.53 ± 15.49, p < 0.001). The average VCO₂ measured by manual gas collection was not significantly different than VCO₂ measured by the metabolic cart (211 ml/min vs 199 ml/min, respectively).

Comparison between energy expenditure calculated by the corrected Harris-Benedict equations and the total energy expenditure as measured by IC is illustrated in Figure 3. There is a significant correlation with an r value of 0.66 (slope = 0.83 ± 0.21, intercept = 116 ± 416, p < 0.01).

Figure 4 compares energy expenditure as measured by IC to CEE. Again, there is a significant correlation with an r value of 0.95 (slope = 1.03 ± 0.08, intercept = 120 ± 137, p < 0.001).

Based on the 95 percent limits of agreement, calculations by HBc would be expected to overestimate caloric requirements by as much as 840 kcal and underestimate by as much as 236 kcal/d. The variability in CEE is less than half of the variability expected from HBc, with the potential to overestimate by 310 kcal and underestimate by 76 kcal/d.

**DISCUSSION**

The results showing a marked discrepancy between HBc and measured energy expenditure by IC are in agreement with previously reported studies. By using simple measurements of expired carbon dioxide and VE, this discrepancy can be dramatically reduced and a reasonably accurate estimate for energy expenditure can be obtained at low cost.
Start-up costs for a metabolic cart are significant. Current pricing for a metabolic cart as of this writing ranges from $25,000 to $33,000. The time involved in setting up a metabolic study can also be considerable. Our average time per metabolic study was approximately 1 h, including a 30-min sampling time, time to move the machine, and time for calibration. In comparison, measurement of VCO₂ can be done fairly expeditiously (usually less than 15 min) and requires no initial outlay for new equipment. Most modern arterial blood gas analyzers can read expired gases with minimal effort. Spirometric measurements of expired lung volumes are performed routinely as a part of ventilator management. The time required for the CEE measurement is minimal and the calculation even simpler than that of Harris-Benedict.

For optimal results in measuring and interpreting CEE, several methodologic points must be addressed.

1. Steady State

Since CEE has been verified as a measurement of caloric requirements against the standard of indirect calorimetry, it can only be assumed to be accurate if the patient is in steady state. With IC measurements, steady state is definable in terms of fluctuations in V₀₂ and VCO₂ as well as measurements of R. Since our technique does not follow a measurement over time, non-steady-state conditions may be present but not detectable. Non-steady-state conditions could be defined in terms of fluctuations of VCO₂; however, multiple measurements would be required. The three patients who did not have interpretable calorimetry results (because of non-steady-state conditions) are shown at the bottom of Table 1. The calculated energy expenditures differ from those predicted by the corrected Harris-Benedict equations. We cannot compare these measurements with IC as the latter is not accurate in these patients. Nevertheless, the results obtained from VCO₂ measurements are close enough to HB that following a caloric prescription based on this measurement could be expected to be no worse than following one based on HB, or for that matter, IC.

2. Single Measurement Artifact

Using a single measurement of expired gas to estimate daily caloric needs could lead to error from sampling artifact. We have shown that if care is taken in patient selection, the error is acceptably low. Similar problems can occur with IC; however, it is much easier to perform serial measurements with CEE than with IC.

3. Respiratory Quotient

The respiratory quotient is not measured using this technique. This measurement can be quite useful in evaluating substrate utilization as well as detecting hepatic lipogenesis or ketosis.

There are two reasons why CEE should differ from IC—variability in the estimation of VCO₂ and an actual R different than 0.83. The choice of an R of 0.83 is somewhat arbitrary. Mixed substrate metabolism has an average R of 0.80 to 0.85. The mean value for R in an ICU...
setting has been reported to run as high as 0.87, although the mean value for R in our study was actually lower at 0.80.

Since the equation assumes that R is 0.83, the equation should be less predictive when the actual R is at the extremes of the physiologic range. If a patient has an actual R of 0.67 (a ketogenic or fasting patient for example), then the CEE would be predicted to overestimate caloric requirements by as much as 19 percent:

\[
K = 3.9 + 1.1R \\
K = 4.29 \\
\text{CEE} = K/6.76 = 6.403 \times V_{CO2}
\]

correcting \( V_{CO2} \) in L/d to ml/min and correcting ATPS to STPD
\( \text{CEE} = 11.06 \times V_E \times PeCO2 \)

the expected error would then be
\[
\frac{9.2 - 11.06}{9.27} = 0.19
\]

Similarly, if we substitute an R of 1.2, the CEE would be predicted to underestimate caloric requirements by approximately 25 percent. This is not an extreme miscalculation and could be self-correcting with repeated measurements. For example, an overfed patient receiving 3,000 kcal/d who has an actual caloric requirement of 2,000 kcal/day and an R of 1.2 (as measured by a metabolic cart) would be predicted to have a CEE of 1,560 kcal/day. Downward adjustment of dietary intake would lead to correction of the respiratory quotient to more physiologic levels and thus closer approximation of CEE to the true caloric requirements with repeated measurement. Most of our patients’ respiratory exchange ratios were closer to the physiologic norm for mixed substrate metabolism, so we would expect the error to be relatively small.

Variability of \( V_{CO2} \) measurements may occur due to a number of factors. Expired gas measurement with a neoprene balloon is usually performed over a shorter period of time than metabolic cart measurement and therefore may not reflect steady-state \( CO2 \) production. Moreover, both the mechanical spirometer and the pneumotachometer on the metabolic cart can vary in accuracy, especially at low flow rates, leading to equally valid, but different measurements of \( V_E \).

Despite these caveats, this simple method has been shown to have better agreement with IC than using standard calculations and gives a clinically useful approximation of caloric expenditure at minimal cost and effort. While not a substitute for IC, this equation may prove to be a useful tool in settings where limited technician time and fiscal restraints preclude the purchase or frequent use of a metabolic cart.

**APPENDIX**

The alveolar ventilation equation\(^{15} \) states

\[
VA = \frac{V_{CO2}}{PaCO2} \times K
\]

therefore

\[
V_{CO2} = \left( VA \times PaCO2 \right)/K
\]

where \( VA \) is minute alveolar ventilation, \( PaCO2 \) is the partial pressure of carbon dioxide in the alveolus, and \( K \) is a conversion factor correcting measurements of alveolar ventilation and \( PaCO2 \) from body temperature and pressure saturated (BTPS) to standard temperature and pressure, dry (STPD).

Because all expired carbon dioxide comes from alveolar gas,\(^{15} \)

\[
VT \times FE \times CO2 = VA \times FA \times CO2
\]

Since the partial pressure of a gas is proportionate to its concentration

\[
VT \times P_Co2 = VA \times PaCO2
\]

multiplying both sides by respiratory rate

\[
V_e \times P_Co2 = VA \times PaCO2
\]

Since \( V_{CO2} = (VA \times PaCO2)/K \), then

\[
V_{CO2} = (V_E \times PaCO2)/K
\]

Since \( V_{CO2} \) is measured at STPD and our measurements of \( V_E \) and \( PeCO2 \) were at ambient temperature and pressure (ATPS), and assuming that average ambient conditions are a barometric pressure of 760 mm Hg, a temperature of 22°C, and a vapor pressure of 20 mm Hg, then by the general gas law

\[
V_{sv} = \frac{(760 - 0.20 \times 273)}{295 \times 760} \times V_{sv}
\]

\[
V_{sv} = 0.901 V_{sv}
\]

therefore

\[
V_{CO2} = (V_E + PeCO2)/0.901
\]

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