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Methods for Estimating Energy Expenditure in Critically Ill Adults

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Abstract

Energy expenditure (EE) is the sum of metabolic activity within the body at a given time and comprises basal EE, diet-induced thermogenesis, and physical activity. In the intensive care unit, EE is most often assessed to determine a patient's caloric requirements. Energy expenditure also may be useful to understand disease states and the metabolic impact of interventions. Several methods for estimating EE are relevant for clinical use, including indirect calorimetry, predictive equations, exhaled carbon dioxide volume, and the Fick method. Indirect calorimetry is the preferred method for evaluating EE and is considered the gold standard for estimating EE in hospitalized patients. However, use of indirect calorimetry is not always practical or possible. Therefore, other methods of estimating EE must be considered. In this review, methods of evaluating EE in critically ill adults are examined and the benefits and limitations of each method are discussed, with practical considerations for use.

Keywords

energy expenditure; indirect calorimetry; metabolism; nutrition

Energy expenditure (EE) is an assessment of whole-host cellular metabolic activity in the body and can be expressed as either kilocalories or kilojoules per day.^{1,2} During critical illness, EE may be affected by many factors, including severity of illness, an individual's underlying health, and pharmacologic interventions.^{3,4} Assessment and monitoring of EE are useful in this population for determining caloric need and to evaluate the metabolic effect of interventions during patient care. In the intensive care unit, EE can be estimated in

patients receiving mechanical ventilatory support using predictive equations, volume of exhaled carbon dioxide, the Fick method, or indirect calorimetry (IC). The choice of method for estimating EE should be considered on the basis of the indication for use, available equipment, and the availability of patient information required to perform the assessment. Knowledge of each method's components and limitations is also important. The purpose of this review is to examine relevant methods for evaluating EE in critically ill adults and discuss the benefits and limitations of each method with practical considerations for use.

Energy Expenditure

Total daily EE encompasses 3 main components: basal energy expenditure (BEE; also known as basal metabolic rate), diet-induced thermogenesis, and physical activity. In healthy individuals, BEE constitutes approximately 70% of total EE and represents the lowest rate of energy expended to maintain basic autonomic function when at rest.^{5,6} For hospitalized patients, BEE makes up greater than 80% to 90% of total EE, particularly for those who are immobile and critically ill.⁵ BEE varies widely between individuals on the basis of age, sex, body composition, hormonal balance, level of circulating catecholamines, and genetics.^{5,7} Basal energy expenditure is also affected by level of fitness, body temperature, medications, and illness severity. Diet-induced thermogenesis, or the thermogenic effect of food, is the amount of energy required to digest nutrients and makes up approximately 10% of total EE.^{6,8} Physical activity is the amount of energy expended from daily activities, movement, and exercise.⁵ Physical activity for most critically ill patients is minimal; therefore, the amount of energy expended in this category is a small portion of total daily EE.

The measurement of BEE requires precise conditions, such as 8 hours of sleep followed by 12 hours of fasting while seated in a recumbent position with minimal interruptions.⁵ Because of the rigorous measurement requirements, actual measurement of BEE is not practical in most clinical settings. Alternatively, resting energy expenditure (REE) is a measurement of EE when an individual is at rest, and REE does not require the strict conditions needed for BEE assessment. For most clinical measurements, REE is estimated and is expressed as the number of kilocalories expended per 24 hours (or per day) to maintain the current resting metabolic state. In addition, REE is generally within 10% of BEE for healthy individuals, making REE a suitable and accessible alternative to BEE in the clinical setting.^{5,8} Although the terms REE and BEE are often used interchangeably, the difference in the rigor of measurement is an important distinguishing factor to recognize.

EE can be estimated using predictive equations or calculated from components of metabolism. Predictive equations are largely based on regression models of individual characteristics such as age, sex, weight, and height and are discussed in detail later in this article. In contrast, EE can also be calculated from measurements of oxygen consumption (V_{O_2}) and carbon dioxide (CO_2) production (V_{CO_2}) using the Weir equation, with or without urinary nitrogen values (Table 1). Oxygen consumption can be calculated by subtracting the volume of expired oxygen from the volume of inspired oxygen, or from the difference in arterial and mixed venous oxygen saturation. Carbon dioxide is a byproduct of metabolic reactions and is largely eliminated via the respiratory tract. Carbon dioxide production can be measured as the volume of expired CO_2 (in liters/min). Urinary nitrogen excretion

represents protein oxidation and usually contributes less than 5% of EE.¹ Most often, nitrogen is excluded from EE assessment but may represent a larger proportion of EE in persons with high protein catabolic states, such as those with a prolonged critical illness.^{5,9} The ratio of V_{CO_2} to VO_2 , referred to as the respiratory quotient (RQ), provides information related to substrate-specific oxidation and energy balance. In general, an RQ greater than 1.0 represents lipogenesis, and an RQ less than 0.7 represents lipolysis.⁵ An RQ between 0.7 and 1.0 indicates mixed substrate metabolism.

There are several other approaches for estimating EE, including calculations from heart rate, direct heat loss, doubly labeled water, activity logs, kinematic measurements, electromyography, total collection systems, and direct calorimetry. These approaches are either not relevant for clinical practice or have not been validated for routine use in the intensive care unit and, therefore, are not included in this review.

Indications for Use of Energy Expenditure

Energy expenditure is a surrogate measure for cellular metabolic activity and can be used for various purposes during critical illness. First, EE is most often used to predict caloric needs for hospitalized patients.^{3,4} For nutritional support, measured EE is usually assessed as the mean value of a short time interval (10-30 minutes), which is then extrapolated over 24 hours to estimate total daily caloric requirements. If EE is estimated from predictive equations, patient data from the chosen equation will be imputed to determine 24-hour caloric requirements.

Second, values obtained from EE measurements can be used to estimate substrate-specific oxidation of proteins, carbohydrates, and fats.¹⁰ Substrate-specific oxidation can assist in determining the optimal amount of macronutrients needed to individualize the nutrition support regimen. To fully assess macronutrient needs, however, additional tests, such as urea nitrogen balance, are required.

Third, EE may be measured as a means of understanding how disease states or acute illness affect metabolism. Identifying metabolic changes associated with altered, and often dynamic, physiologic states may be an important tool to better recognize condition-specific metabolic patterns and evaluate the potential influences of commonly applied strategies designed to improve clinical outcomes.¹¹⁻¹⁴ For example, EE can be used to understand how fluctuations in blood glucose levels during diabetic ketoacidosis affect protein and carbohydrate metabolism to determine optimal nutrition support across the acute illness period.

Finally, EE can be assessed to evaluate the metabolic effect of specific medications or interventions. For example, EE can be used to determine the metabolic impact of hypothermia during targeted temperature management after cardiac arrest, which may enable a better understanding of how this intervention provides neurologic benefit.¹¹ A limitation of EE, however, is that it reflects total body metabolism, and it is not possible to determine metabolic alterations of a single organ or body system. The choice of EE

assessment method is driven by the equipment available, need for accuracy of actual EE, need for static or continuous measurement, and the intended use of EE values.

Methods of Assessing Energy Expenditure

Indirect Calorimetry

Calorimetry is the measurement of the amount of energy produced from endothermic and exothermic activities resulting from metabolism of fats, carbohydrates, and proteins.^{15,16} The breakdown of these substrates during metabolism consumes oxygen and releases CO₂ and heat. Direct calorimetry measures actual heat loss and is the most exact method for determining EE but requires extensive equipment and expertise that is not practical for use in clinical settings.^{3,15} Conversely, IC is widely used to assess EE in hospitalized patients. IC measures exhaled CO₂ and oxygen to calculate EE. Indirect calorimetry is considered the gold standard method of measuring EE in hospitalized patients to determine caloric needs and is sometimes referred to as a “metabolic cart” study.^{3,4} Indirect calorimetry provides highly specific information regarding EE, oxygen consumption, and substrate-specific use. There are several IC devices on the market that can be used for patients regardless of whether they are receiving mechanical ventilatory support or are spontaneously breathing.

Indirect Calorimetry Systems.—There are 2 types of IC systems: closed and open circuit. In a closed circuit, the patient breathes from a closed air system of known volume to measure Vco₂ and Vo₂. Closed circuits are rarely used in clinical practice currently. Conversely, open-circuit IC is widely used in modern systems. In open-circuit systems, the patient inhales ambient air and the expired gases are analyzed using dilution, mixing chambers, or breath-by-breath systems (Figure 1).¹⁷ Dilution methods use a bias gas (usually room air) to move the patient’s exhaled air through the circuit for sampling. The bias flow is of known concentration and volume and is not included in EE analysis. Mixing-chamber systems homogenize the patient’s exhaled air, and the gases are sampled from the IC chamber. Breath-by-breath systems sample the patient’s expired air for each breath, and EE is usually displayed as a function of the average EE over several breaths.

Because it is difficult to measure the difference between the volumes of inspired and expired air, open-circuit IC uses the Haldane transformation to estimate the volume of inspired air from exhaled volumes.^{16,18} The Haldane transformation assumes the volume of nitrogen is constant between inhalation and exhalation to calculate inspired volumes. Because the denominator is 1 minus the fraction of inspired oxygen (Fio₂), higher values of Fio₂ cause the denominator to approach 0 and result in a Vo₂ of infinity (ie, unmeasurable). Calculations when a patient’s Fio₂ is greater than 0.6 have higher error rates, and Vo₂ cannot be accurately calculated at a Fio₂ of approximately 0.85 or greater, depending on the device used.^{3,16}

Open-circuit IC can be used for both spontaneously breathing patients and those receiving mechanical ventilatory support. For spontaneously breathing patients, expired gases can be captured using a mouthpiece, face mask, face canopy, or face tent.⁵ Some models pump a constant flow of air through the system, whereas others allow the patient to breathe ambient air. Care must be taken to avoid allowing patients to rebreathe expired CO₂. If rebreathing

occurs, EE calculations will be inaccurate due to misassumptions from V_{CO_2} calculations. For patients receiving mechanical ventilatory support, an open-circuit IC system is required to enable measurement of variable F_{IO_2} . Indirect calorimetry devices use either sampling ports attached to both the inspiratory and expiratory limbs of the ventilator or connect at a single point near the patient's endotracheal tube.^{8,18} Often, a single standalone system can assess EE for spontaneously breathing patients as well as those receiving mechanical ventilatory support.

Gas Analyzers.—The volume of exhaled carbon dioxide is most often measured using nondispersive infrared sensors that consist of a spectroscopic sensor to measure adsorption of the infrared wavelength specific to CO_2 .^{1,19} Attenuation of the CO_2 wavelength determines concentration of V_{CO_2} . In most modern devices, oxygen is measured using either a paramagnetic or galvanic oxygen sensor. Paramagnetic sensors rely on the paramagnetic properties of oxygen whereby oxygen is attracted to a magnetic field within the analyzer, and the amount of pressure or current displaced is proportional to the concentration of oxygen within the gas mixture.^{1,20} Galvanic fuel oxygen sensors use a flow of electrons that is proportional to the concentration of oxygen.

Benefits and Limitations of Indirect Calorimetry.—Indirect calorimetry is considered the gold standard to assess EE because it provides the most accurate assessment of EE in clinical settings.² Indirect calorimetry can be used for both spontaneously breathing patients and patients receiving mechanical ventilatory support and is the only plausible method for assessment of acute fluctuations in EE or measurement of EE over prolonged periods. Patients with a chest tube and air leak, pneumothorax, or a respiratory rate greater than 35 breaths/min would likely render IC measurements inaccurate. For patients receiving mechanical ventilatory support, having a positive end-expiratory pressure greater than 12 mm Hg, F_{IO_2} greater than 0.6, ventilator humidification, concomitant inhaled nitric oxide, controlled mechanical ventilation rates with patient-initiated breaths, or leaks in the ventilator system will decrease measurement accuracy.^{4,18,21} Each IC device varies, so it is imperative that the clinician is knowledgeable and trained in the use of selected equipment when performing the test and interpreting the results.

There is large variability in agreement of EE values reported from studies in which IC devices have been compared with one another.^{22–25} Inconsistency in agreement between devices could be due to the location of gas sampling on the ventilator circuit or may reflect differences in devices that use a mixing chamber compared with breath-by-breath analysis. Studies with nonsimultaneous comparisons may reflect metabolic fluctuations rather than true device inaccuracies. Historically, modern IC devices have been compared with the Deltatrac II (Datex-Ohmeda), which has long been considered the most accurate IC device. With improved technology of modern IC devices, it is reasonable to question the continued practice of comparing agreement and device validity with the Deltatrac II, particularly because the Deltatrac II is no longer manufactured or supported.^{24,26} In addition, when level of agreement between devices is compared without a reference or definitive measure of EE (eg, a Douglas bag), it is difficult to determine if either device reflects true EE or just a function of technique. The observed variability in agreement of true IC values highlights the

importance of clinicians critically evaluating each IC device before use and having a thorough understanding of proper technique and measurement limitations.

Despite inherent device variability, IC is still considered the gold standard for assessing EE in hospitalized and critically ill patients when determining caloric requirements. It is plausible that IC would also be the preferred method for measuring EE in relation to assessment of real-time fluctuations in metabolic rates, and IC has been used for this purpose in several clinical studies.^{11,12,14,21,27,28} Although useful for understanding EE, IC represents total body metabolic activity and, therefore, does not provide information related to organ-specific differences in metabolism. Also, IC devices are sensitive to measurement error, require user expertise, and can be time consuming to set up. Finally, IC devices can be expensive, which may be a limiting factor for routine use in some clinical settings, although newer, more affordable models are in development. Table 2 highlights the benefits and limitations of each method for estimating EE.

Predictive Equations

More than 200 equations have been proposed to estimate EE, most of which have not been validated for use in critically ill patients.¹⁸ Some of the most commonly used predictive equations in critical care are the Harris-Benedict equation, American College of Chest Physicians weight-based method, Mifflin-St Jeor equation, Ireton-Jones equations, and the Penn State equation (Table 3).^{3,29–38} The primary purpose of these equations is to estimate REE to guide nutritional therapy.² Predictive equations largely use anthropometric measurements, such as height and weight, and other patient data, such as age and sex, to predict caloric needs over 24 hours. Equations designed for hospitalized patients often take into account illness severity and/or mechanical ventilation; however, many equations, such as the Harris-Benedict equation, were designed for use in healthy persons with a stable body weight and are less suitable for use in critical illness.

When compared with actual measurement of EE using IC for critically ill patients in the intensive care unit, predictive equations mostly have had poor agreement (> 10% variability) in predicting REE compared with measured values.^{7,29,31,39–45} This lack of agreement is especially evident when stratified by body mass index, age, and illness severity.^{43,46–48} Obesity is a major confounding factor in determining predictive equation bias (ie, over- or underpredicting measured values) and accuracy. For instance, in a recent study, predictive equations, compared with measured energy requirements, underestimated EE in critically ill, obese patients.⁴⁸ Because many critically ill patients are obese, are in varying states of illness, and diverse in age and sex distribution, it is challenging to apply any single equation to all patients.^{31,46,49,50} Therefore, it is necessary to carefully consider which equation is best suited for the population of interest. For example, the energy needs of a patient receiving ventilatory support who has burn injuries are likely very different from a stable medical patient, and each may require a different predictive equation.

One equation with higher demonstrated accuracy (70%-75%) when compared with measured EE is the Penn State equation, although results vary by patient age and obesity status.^{34,43,51} The Academy of Nutrition and Dietetics recommends using the Penn State equation in critically ill adults with mechanical ventilation when actual measurement of EE

is not available, whereas the American Society for Parenteral and Enteral Nutrition guidelines do not recommend a specific equation.^{2,52}

Benefits and Limitations of Predictive Equations.—Predictive equations are easily accessible online and generally do not require complex data collection or invasive monitoring to estimate REE. Although predictive equations are practical, their use in accurately predicting REE in critically ill patients is limited. Choosing the optimal equation for the population of interest may also present challenges, especially when there is a risk for overestimation of caloric need, because overfeeding has been associated with worse clinical outcomes and death.^{53–55} In addition, most equations over- or underpredict REE for people at extremes of weight, older adults, and nonwhite persons.^{5,30,49} Patient-specific illnesses, such as acute kidney injury, can also cause predictive equations to be inaccurate compared with measured EE.¹⁰ The most promising predictive equation for critically ill adults is the Penn State equation; however, this only provides a static estimation of REE and would not be appropriate for understanding acute fluctuations in energy production.

Because critically ill patients likely have highly variable metabolic expenditures over their hospital course, predictive equations should be used with caution as a surrogate for measured EE in this population. Furthermore, predictive equations should not be used when the goal is understanding dynamic components of EE through stages of an intervention or illness.

Exhaled CO₂

Recently, it has been hypothesized that using Vco₂ alone could be used to estimate EE. The volume of exhaled CO₂ can be measured using end-tidal carbon dioxide (EtcO₂), or capnography. End-tidal carbon dioxide is the maximal concentration of expired CO₂ at the end of each breath and can be displayed as a total volume over 1 minute (Vco₂).^{56,57} End-tidal carbon dioxide is often used during mechanical ventilation to monitor acute changes in breathing or physiologic states. End-tidal carbon dioxide measurement may be integrated within a mechanical ventilator system or may be measured via a standalone system. Although it is possible to measure EtcO₂ in spontaneously breathing patients, measurement values are highly variable and, therefore, are not recommended to estimate EE.^{58,59}

Either a fixed or a macronutrient-based RQ is used to estimate EE by Vco₂.^{60–64} In either case, the Weir equation is modified to replace Vo₂ with Vco₂/RQ to calculate EE. In a study of 79 pediatric patients receiving mechanical ventilatory support, steady-state EE from IC was used to derive a mean RQ (0.89).⁶¹ A subsequent validation group of 94 patients receiving mechanical ventilatory support was used to test the accuracy of the modified equation compared with both a predicted equation and measured EE. Compared with measured EE, the modified Weir equation was more accurate (bias, -0.6%; limits of agreement, -14.4% to 13.1%) compared with the predictive equation (bias, 0.1%; limits of agreement, -40.5% to 40.6%) but demonstrated greater variability as the measured RQ moved away from 0.89 in either direction.

Similarly, in a study of adults receiving mechanical ventilatory support, where mean 24-hour EE determined from IC was compared with EE derived from simultaneous ventilator-derived

CO₂ and predictive equations, a nutritionally based RQ was determined by calculating macronutrient intake (assumed an RQ of 1 for carbohydrates, 0.7 for fats, and 0.8 for protein) and so was not a fixed value.⁶² The RQ was a weighted average of total macronutrient intake over 24 hours. Similar to the pediatric study, the modified Weir equation using a ventilator-derived CO₂ value was more accurate than predictive equations (61% compared with 31%-54%) and had an acceptable bias of 7.7% when compared with EE determined from IC.⁶¹

In another retrospective study of 80 adults receiving mechanical ventilatory support, the authors compared measured EE using IC with a calculated EE, where the RQ was fixed at 0.8, 0.85, and 0.89.⁶⁴ For all RQ values, the authors found an unacceptable level of agreement between calculated EE using fixed RQ and the measured EE using IC. In addition, in a retrospective study of 278 adults receiving mechanical ventilatory support, authors compared both a fixed RQ and a nutritionally based RQ with IC and found approximately 23% of Vco₂-derived EE values were greater than the 10% variability threshold for both RQ calculations.⁶³ When accuracy was compared at a 5% variability threshold, approximately 54% of values were outside the range for both RQ calculations.

Benefits and Limitations of Vco₂—Expired CO₂ may be a promising method to estimate EE, and a Vco₂ value is easily obtained using noninvasive monitoring. In addition, many hospital systems already have Etco₂ technology, and several ventilator models offer built-in Etco₂ capabilities. Conversely, Vco₂ may not allow for enough flexibility to account for the wide range of physiologic complexities and metabolic fluctuations that occur during illness trajectories, and correlation with measured EE is variable between studies.^{56,61,63,64} Altered adsorption of nutrients or differences in fed versus fasting states may increase RQ variability, leading to inherent inaccuracies in the modified equation using a fixed or calculated RQ. Although early results are encouraging, more research is needed before global adoption of Vco₂ is used to estimate EE in clinical settings. In addition, this method has not been validated for use in understanding clinical states or sensitivity to acute metabolic fluctuations.

Fick Method

The Fick equation was originally developed as a way to estimate cardiac output using oxygen consumption principles.³¹ Reversing the equation, it is possible to estimate EE from measured cardiac output, hemoglobin, arterial oxygen saturation, and mixed venous oxygen saturation; this is called the Fick method.^{65,66} The Fick method is sometimes referred to as “respiratory indirect calorimetry” and is limited to patients with a pulmonary artery (PA) catheter because of the need for mixed venous oxygen measurements.

To estimate EE, the following equation is used, where CO is cardiac output, Hb is hemoglobin concentration, Sao₂ is the percentage of oxygen bound to hemoglobin (ie, arterial oxygen saturation), and SvO₂ is central mixed venous oxygen saturation:

$$EE = CO \times Hb \times (Sao_2 - SvO_2) \times 95.18$$

When compared with IC, correlation and agreement of the Fick method to estimate EE are highly variable between studies, and the method has largely fallen out of favor in more recent years for estimating EE.^{39,67–70} Also, it is unclear whether the Fick method truly represents total-body EE or actually overrepresents pulmonary metabolism.

Benefits and Limitations of the Fick Method.—For patients with an existing PA catheter, assessment of EE using the Fick method is easy to calculate using frequently obtained patient measurements. For most patients in the intensive care unit today, PA catheters are used infrequently, and it would not be advantageous to place a PA catheter for EE assessment alone. In addition, EE calculations may be prone to inaccuracies if cardiac output and mixed venous oxygen saturation are incorrectly measured. Because of inconsistencies in accuracy and the requirement of invasive monitoring, the Fick method is not recommended for routine assessment of EE in critically ill adults. The Fick method is sometimes used in research applications as a comparator to IC.⁷¹

Conclusion

Assessment of EE in critically ill adults is an important component of nutritional therapy and may be useful in understanding metabolic influences of pathophysiological conditions and acute metabolic impacts of interventions. Several methods can be used to estimate EE, and each method requires careful consideration to determine if it is appropriate and feasible for the given scenario. The gold standard for estimating EE in critically ill adults is IC. Although IC use can be technically challenging, with a risk of bias estimates if performed incorrectly, it is the preferred tool to measure EE whenever possible. When IC is unavailable, or when the patient's condition limits IC accuracy (eg, $\text{Fio}_2 > 0.6$ or pneumothorax), alternative methods for estimating EE must be considered. Predictive equations should be used when IC is unavailable. However, these equations are consistently inaccurate across multiple populations and should be used with caution during critical illness. If predictive equations must be used, the Penn State equation may provide the most accurate assessment of EE; however, a predictive equation appropriate for the population of interest should be considered. At the very least, care should be taken to avoid overestimation of energy requirements, because overfeeding may contribute to worsening patient outcomes. Newer methods for estimating EE, such as exhaled Vco_2 with a derived RQ, may allow for continuous and inexpensive assessment of EE, but results are preliminary and need additional validation in critically ill populations. Assessment of EE should be part of standard clinical care to guide nutritional support and may be used to deepen the understanding of critical illness and the effect of interventions on metabolism.

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Figure:

Indirect calorimetry for spontaneously breathing patients and patients receiving mechanical ventilatory support. (a) Breath-by-breath example where expired gases are measured for each breath by gas analyzers and flow meters connected to the ventilator circuit nearest to the patient. (b) Mixing chamber example where oxygen concentration of inhaled air (F_{iO_2}) is measured via the inspiratory limb of the ventilator. Exhaled gas is collected in the mixing chamber, where it is analyzed for oxygen (FeO_2) and carbon dioxide ($FeCO_2$) average concentrations. Gas is eliminated from the mixing chamber using a constant flow generator that dilutes the gas from the mixing chamber (F_{ed}). (c) Canopy example for spontaneously breathing patients (1: flow analysis, 2: F_{iO_2} , 3: $FiCO_2$, 4: FeO_2 , 5: $FeCO_2$, 6: $F_{ed}CO_2$, 7: $F_{ed}O_2$; small arrows: respiratory gas flow, solid line: gas sampling, dotted line: signal for flow analysis, small arrows: respiratory gas flow, bold arrow: constant flow). Reprinted from Oshima et al,¹⁷ with permission from Elsevier.

Table 1:**Equations Used to Calculate Energy Expenditure From Expired Gases**

Equation	Purpose	Calculation
Weir equation	To calculate EE using expired CO ₂ and O ₂	With urinary nitrogen: $EE \text{ (kcal/d)} = [(3.94 \times V_{O_2}) + (1.11 \times V_{CO_2})]1.44 - 2.17(UN)$ Excluding urinary nitrogen: $EE \text{ (kcal/d)} = [(3.94 \times V_{O_2}) + (1.11 \times V_{CO_2})]1.44$
Respiratory quotient	Reflects substrate use	$RQ = V_{CO_2} / V_{O_2}$ (using Haldane transformation)
V _{O₂}	Determine O ₂ consumption	$V_I(F_{IO_2}) - V_E(Fe_{O_2})$
V _{CO₂}	Determine CO ₂ production	$V_E(Fe_{CO_2}) - V_I(Fi_{CO_2})$
Haldane transformation	Estimate V _I when using open circuit indirect calorimetry	$(1) V_I = (FeN_2 / FiN_2) V_E$ $(2) FeN_2 = 1 - Fe_{O_2} - Fe_{CO_2}$ $(3) FiN_2 = 1 - Fi_{O_2} - Fi_{CO_2}$ $(4) V_{O_2} = [(1 - Fe_{O_2} - Fe_{CO_2}) \times (Fi_{O_2} - Fe_{O_2}) V_E] / (1 - Fi_{O_2})$

Abbreviations: CO₂, carbon dioxide; EE, energy expenditure; FeCO₂, fraction of expired carbon dioxide; FeN₂, fraction of expired nitrogen; FeO₂, fraction of oxygen in expired air; FiCO₂, fraction of inspired carbon dioxide; FiN₂, fraction of inspired nitrogen; FiO₂, fraction of inspired oxygen; kcal, kilocalories; O₂, oxygen; RQ, respiratory quotient; UN, urinary nitrogen; V_{CO₂}, carbon dioxide production (L/min); V_E, volume of exhaled gas (L/min); V_I, volume of inhaled gas (L/min); V_{O₂}, oxygen consumption (L/min).

Table 2:**Benefits and Limitations of Methods for Estimating Energy Expenditure**

Method	Benefits	Limitations	Applications
Indirect calorimetry	Gold standard and most precise measure of EE May be integrated in new mechanical ventilators Useful in patients who are on ventilators and those who are not	Technically challenging and may be inaccurate if measured incorrectly Variability in values between devices	Can be used to determine caloric requirements or to evaluate clinical states or interventions
Predictive equations	Easily accessible equations No cost	Often inaccurate during critical illness, especially when stratifying by body mass index and age Not adaptable for dynamic physiologic states	Use when IC not available Penn State equation may be most accurate, depending on the population
Exhaled CO ₂ (Etco ₂)	Often integrated in existing ventilators Low cost	Limited studies validating usefulness Complex calculation of EE with nutritional RQ	May be a viable option to estimate EE, pending further research
Fick method	Easily available calculation Can measure dynamic EE measurements	Limited use of pulmonary artery catheters May overrepresent pulmonary artery metabolism	May be of use when pulmonary artery catheter is in place and IC is not available Not a widely used method in clinical care

Abbreviations: CO₂, carbon dioxide; EE, energy expenditure; Etco₂, end-tidal carbon dioxide; IC, indirect calorimetry; RQ, respiratory quotient.

Table 3:**Predictive Equations Commonly Used for Critically Ill Adults**

Equation	Calculation (kcal/d)
Harris-Benedict ³⁸	Male: $66.473 + (13.7516 \times \text{weight [kg]}) + (5.003 \times \text{height [cm]}) - (6.755 \times \text{age [y]})$ Female: $655.0955 + (9.5634 \times \text{weight [kg]}) + (1.8496 \times \text{height [cm]}) - (4.6756 \times \text{age [y]})$
ACCP ^{30,32}	$\text{BMI}^a < 25$: actual body weight ^b $\times 25$ $\text{BMI}^a \geq 25$: ideal body weight ^c $\times 25$
Mifflin-St Jeor ³⁵	Male: $(10 \times \text{weight [kg]}) + (6.25 \times \text{height [cm]}) - (5 \times \text{age [y]}) + 5$ Female: $(10 \times \text{weight [kg]}) + (6.25 \times \text{height [cm]}) - (5 \times \text{age [y]}) - 161$
Ireton-Jones ^{36,37}	Mechanically ventilated: $1784 - (11 \times \text{age [y]}) + (5 \times \text{weight [kg]}) + (244, \text{ if male}) + (239, \text{ if trauma present}) + (840, \text{ if burn present})$ Spontaneously breathing: $629 - (11 \times \text{age [y]}) + (25 \times \text{weight [kg]}) - 609 \text{ (when BMI} > 27^a)$
Penn State ^{33,34}	2003a: $0.85 \text{ (Harris-Benedict equation)} + (175 \times T_{\text{max}}) + (33 \times \text{Ve}) - 6433$ 2003b: $0.96 \text{ (Mifflin-St Jeor)} + 31(\text{Ve}) + 167(T_{\text{max}}) - 6212$ 2010: (for age 60 years, BMI 30 ^a): $0.71(\text{Mifflin-St Jeor equation}) + 85(T_{\text{max}}) + 64(\text{Ve}) - 3085$

Abbreviations: ACCP, American College of Chest Physicians; BMI, body mass index; T_{max}, maximum body temperature in past 24 hours (°C); Ve, volume of exhaled gas (L/min)

^aCalculated as weight (kg) divided by height squared (m²)

^bWeight (kg) on hospital admission.

^cMen: $50 \text{ kg} + (2.3 \text{ kg/in} \times (\text{in} - 60))$, women: $45.5 \text{ kg} + (2.3 \text{ kg/in} \times (\text{in} - 60))$.