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Energy

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CONTENTS

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Objectives

Compare energy metabolism during health and illness.

Identify evidence-based methods for calculating resting metabolic rate (RMR).

Review methods to measure energy expenditure.

Test Your Knowledge Questions

1. Which of the following is the largest component of total energy expenditure (TEE)?

A. RMR
B. Thermogenic effect of digestion
C. Physical activity
D. Metabolic stress

2. Which of the following is the most commonly used method for assessing energy expenditure?

A. Indirect calorimetry (IC)
B. Predictive equations
C. The reverse Fick equation
D. Doubly labeled water

3. Which parameter is measured when using IC?

A. Heat loss
B. Catabolic rate
C. Gas exchange
D. Free energy balance

4. You are determining the energy intake target for a 53-year-old, critically ill, male patient who is about to start enteral feeding. He is 170 cm in height and weighs 150 kg. His body mass index (BMI) is 51.9 and his ideal body weight is 70 kg. Body temperature is 37.3 degrees Celsius and minute ventilation is 12.5 L/min. Based on the 2016 American Society for Parenteral and Enteral Nutrition (ASPEN) guideline1 for calculating a goal energy intake for such a critically ill patient, what energy value would you use as the basis for the feeding plan?

A. 1750 kcal/d (25 kcal per kg ideal body weight)
B. 1225 kcal/d (70% of the calculated 25 kcal per kg ideal body weight)
C. 2250 kcal/d (25 kcal per kg adjusted body weight)
D. 2615 kcal/d (Penn State equation)

Test Your Knowledge Answers

1) The correct answer is A. The thermogenic effect of digestion is generally thought to contribute no more than 10% to TEE.[2] Activity contributes 5% to 30% to TEE.[2] With the exceptions of burn (see Chapter 24) and sepsis (see Chapter 23), metabolic stress contributes less than 50% to TEE. However, in almost all situations, RMR constitutes 60% to 75% of TEE.[3]
2) The correct answer is B. Most nutrition support feeding regimens are based on predictive equations used to assess energy expenditure.[4] The measurement of energy expenditure via IC is more accurate than predictive equations but is underused because the equipment is expensive to purchase and operate, and because some patients cannot be measured for various technical and physiological reasons.
3) The correct answer is C. Indirect calorimeters measure respiratory gas exchange (the difference between inspired and expired oxygen and carbon dioxide).[5] If proper testing conditions are observed, respiratory gas exchange is equivalent to metabolic gas exchange (the consumption of oxygen and production of carbon dioxide [CO_2] at the cellular level). Gas exchange data are converted to RMR using the Weir equation.[6]
4) The correct answer is A. The ASPEN guideline states that the goal intake for all classes of obesity should not exceed 65% to 70% of target energy expenditure as measured by IC.[1] For class III obesity (BMI equal to or greater than 40), an intake of 22 to 25 kcal per kg ideal body weight is recommended. The Penn State equation (answer D) has been validated as being among the most accurate ways of calculating energy expenditure up to a BMI of at least 80.[7,8] However, answer D is incorrect if following the ASPEN guideline because that guideline emphasizes the kcal/kg method. The patient has class III obesity; therefore, ideal body weight would be used for the calculation, making answer C incorrect because it uses adjusted body weight. Answer B is incorrect because the guideline already factors the 30% reduction in the energy calculation into the standard; therefore, if the energy expenditure were calculated and then multiplied by 70%, the effect would be to reduce the energy intake target to about 50% of expenditure.

Background

Acquisition and transformation of energy are among the most basic characteristics of life.[9] Living things must be capable of consuming chemical energy from the environment, converting it to cellular components, and transforming it to a form that can power work. Energy transformations (metabolism) are necessary for living things to maintain homeostasis and perform the other activities associated with life. In humans, energy metabolism has evolved into a series of interrelated and complex biochemical processes by which humans consume fuels from the environment, convert them to tissue or oxidize them to release energy to perform work, and ultimately convert the fuels to heat, water, and CO_2, all of which are dissipated back to the environment.

This chapter reviews energy metabolism in healthy subjects as the framework for understanding the alterations in energy metabolism during malnutrition and illness. The energy prescription is a fundamental aspect of the nutrition support regimen. Therefore, emphasis in this chapter is placed on evidence-based methods for determining the energy expenditure of those patients who are unable to meet their needs orally and therefore require nutrition support therapy.

Overview of Energy Metabolism

The basic fuels of the body are carbohydrate, protein, and fat (ethanol can also be oxidized). Glucose is used preferentially after meals, whereas fat is stored for later oxidation. Protein generally is used for structural and functional, rather than oxidative, purposes; however, during routine protein turnover, some is oxidized. (See Chapters 3, 5, and 6.) When energy is not available in the form of food, the body cannibalizes its own tissues as an endogenous energy source. This catabolic process is hormonally driven and is reversible by feeding. The maintenance of an endogenous source of glucose supply while limiting protein loss is of primary importance, and the body has complex mechanisms to create and store glucose if dietary intake is interrupted.10,11 Over time, further metabolic adaptations provide alternate fuels for oxidative pathways that substitute for and recycle glucose and that access the large store of energy in the adipose tissue. These changes decrease protein catabolism and allow conservation of the body protein mass while providing enough energy to maintain core body functions.12–14

Components of Energy Expenditure

TEE can be divided into 3 major components in healthy, well-nourished adults: basal metabolic rate (BMR) or RMR, energy required for the thermogenic effect of digestion, and energy expenditure associated with physical activity. Tissue synthesis is an energy-consuming process, and illness may cause an alteration in rest, thermogenesis, and physical activity.

Basal or Resting Metabolic Rate

The terms BMR and RMR sometimes cause confusion, partly because they have distinct but similar definitions, and partly because some authors use the terms interchangeably. BMR is metabolic rate measured in a fasting state, immediately upon awakening and before any physical activity is undertaken.2,3 RMR also is measured in a fasted state,2,3 but some movement (dressing, walking) is allowed before testing. A rest time of 20 to 30 minutes is necessary for recovery from this level of activity.2,15 Once this rest period is provided, the difference between RMR and BMR is small, with RMR being slightly higher. Because BMR is a more cumbersome measurement (requiring confinement in a metabolic ward or laboratory), most studies of human metabolism are made in a resting rather than a basal state. In many nutrition support patients, even the less restrictive RMR standard of measurement is not obtained because the patients are fed continuously and thus are never in a fasted state. Instead, the resting definition is modified to include the metabolic effect of feeding.3,16

Even in the most physically active individuals and the most hypermetabolic patients, RMR accounts for the largest portion of TEE (60% to 75%). RMR is determined largely by body size and body composition.17,18 Sex and age also affect RMR (RMR is lower in females and in the elderly).18,19 Some of the sex and age effects are indirect, being a result of the amount or composition of the fat-free mass rather than related to biological sex differences or age effects per se.[18,19] Composition of the fat-free mass might also explain some observed racial differences in RMR.[19–21]

Thermogenic Effect of Digestion

The digestion of macronutrients following the consumption of a meal leads to an increase in metabolic rate referred to as the thermogenic effect of digestion. This still ill-defined phenomenon was originally thought to be specific to protein (hence, its original name, “specific dynamic action”).[5] The presence, magnitude, and duration of the thermogenic effect of digestion seem to be influenced by numerous factors. Diet factors include the size and composition of the meal and the time of day the meal is eaten.[2] Other factors include age, smoking, stress, and caffeine use.[2] In general, a 5% to 10% increase in TEE is ascribed to the thermogenic effect of digestion.[13,22] However, Heymsfield and associates[23] have demonstrated in healthy people that if feeding is delivered as a continuous infusion of liquid formula via gastric feeding tube, the thermogenic effect of digestion is not induced. This finding is pertinent to the nutrition support population; the same seems to be true for critically ill patients being fed continuously, although the data are limited. Frankenfield and Ashcraft[24] found only a 1% difference in RMR between fed and unfed patients with brain injuries (1982 ± 249 kcal/d vs 2002 ± 425 kcal/d).

Physical Activity

Physical activity is the most variable and difficult to predict portion of TEE. In nonhospitalized adults, the amount of energy expended on physical activity is a function of the duration and vigor of exercise and nonexercise movement and work, and can be influenced by conscious and unconscious factors.[25,26] For critically ill patients, care activities, such as bathing, turning, wound care, and chest physiotherapy, can substantially raise the metabolic rate. However, these activities are short-lived and their cumulative effect on TEE is usually small. Typical activity in critically ill patients has been measured at about 5% to 10% above rest.[27–29] In hospitalized patients who are ambulatory, agitated, or fidgeting, energy expended in physical activity might be considerably higher than 10%.

Tissue Synthesis

In nutrition repletion, pregnancy, and childhood, energy requirements increase to support tissue growth.[30] Tissue synthesis is a high-energy activity. Not only is the newly synthesized tissue composed of fuel (protein and fat), but the synthesis of the new tissue from individual amino acids, fatty acids, and glucose is an energy-requiring reaction.[30,31] Wound repair may be thought of in a similar way but on a smaller scale.[31]

Illness

Hypermetabolism is often noted in people who are chronically or acutely ill.[7,32–35] Taylor has reviewed many studies of RMR in chronic illness.[32] A common finding in these studies is that the mean increase in RMR is 10% above the healthy resting level. This mean value sits right on the upper edge of the range of “normal” (±10% of the predicted healthy level) and indicates that RMR is not elevated in about 50% of chronically ill patients, whereas it is elevated in the other 50%.

A limited number of studies of RMR have been carried out in acutely ill, spontaneously breathing patients. Gariballa and Forster33 reported that the Harris-Benedict equation for RMR in healthy people approximated the measured RMR in a group of such patients; however, the equation accurately predicted the measured RMR in only 47% of the cases, meaning that the other 53% were either hypermetabolic or hypometabolic (the authors did not describe the distribution). Weijs and colleagues34 measured the RMR of a group of inpatients and found that the Mifflin–St. Jeor equation for healthy people accurately estimated the RMR in 50% of the cases. Frankenfield and Ashcraft35 found a similar accuracy rate for the Mifflin–St. Jeor equation (42%), with a mean elevation in RMR of 17% above Mifflin–St. Jeor equation value.

The RMR of critically ill patients has been measured more extensively than the RMR for perhaps any other group.3 RMR equations for healthy people (primarily Harris-Benedict or Mifflin–St. Jeor) are routinely found to be inaccurate in most critically ill patients, with the direction of the error indicating that most critically ill patients are hypermetabolic. Most metabolic studies of the critically ill group patients by disease type (eg, trauma, surgery, sepsis); however, a clear hierarchy in the degree of hypermetabolism by illness type has not emerged, perhaps because it is the inflammatory response to the illness—rather than the illness itself—that determines the RMR. Thus, a febrile surgical patient may have a higher RMR than an afebrile trauma patient. Frankenfield and colleagues36 found that differences in the RMRs of trauma, surgery, and medical critical care patients were eliminated when the impact of body temperature was controlled. Raurich et al37 likewise found no differences in RMRs among trauma, surgical, and medical patients when RMR was measured at body temperatures between 36 and 38 degrees Celsius.

Table 2-1 shows how measured RMR compares with comparative standards for healthy people in (1) healthy individuals;38 (2) acutely ill, spontaneously breathing patients;35 and (3) critically ill, mechanically ventilated patients.7 In healthy adults, 11% have measured RMR above the expected rate. In acutely ill patients, this figure increases to 60%. In mechanically ventilated, critically ill patients, the measured RMR exceeds the healthy comparative standard 74% of the time. Hypometabolism is rare in all 3 groups but notably less so in ill patients than in healthy people. The maximum increase in RMR is higher in the critically ill than in the healthy or acutely ill groups.

TABLE 2-1 Rates and Degrees of Hypermetabolism and Hypometabolism in Healthy; Acutely Ill; and Critically Ill, Mechanically Ventilated Patients

Group (Reference)	N	% Obese	Mean Resting Metabolic Rate Increase (% of Mifflin-St. Jeor)	Percentage of Measurements >10% Above Mifflin-St. Jeor	Maximum Above Mifflin-St. Jeor	Percentage of Measurements <10% Above Mifflin-St. Jeor	Maximum Below Mifflin-St. Jeor
Healthy (35)	337	46	1.01	11	1.45	6.8	0.83
Acutely ill (38)	56	35	1.17	60	1.54	3.5	0.77
Critically ill (7)	202	47	1.23	74	2.14	1.5	0.75

Overview of Methods to Determine Energy Expenditure

Measurement of Energy Expenditure

A foundational goal of nutrition support is to preserve lean body mass and maintain immune function while avoiding complications related to under- or overfeeding. Despite the availability of more than 200 predictive equations to estimate energy expenditure, predicting the needs of an individual critically ill patient is difficult. Measurement of RMR is the most reliable method of determining energy needs.2,3,16

Direct Calorimetry

Direct calorimetry measures heat and chemical energy released from the body. Because the fuel energy used by the body is ultimately transformed to heat, heat release is considered a direct measurement of metabolic rate. Urine is also collected and measured to account for the small amount of chemical energy lost in urea excretion in urine. Direct calorimeters are sophisticated machines consisting of a living space or chamber thermally isolated from the outside, with equipment to extract and measure the heat released into the air of the chamber from the subject residing within.5 Experiments can last for days, and this method allows for the partitioning of energy expended at rest, in sleep, and during physical activity (which is sometimes tracked using a radar system inside the chamber). Direct calorimetry is most appropriate in the study of healthy subjects done in research and academic environments. The technique is not practical in the patient care because the individual must remain alone in the chamber over an extended time without caregivers or medical equipment (both of which produce heat).

Indirect Calorimetry

Among the first metabolic observations of living things was that they consumed some substance from the atmosphere.5 It was found later that this substance was oxygen and that, furthermore, CO2 was produced. In the late 19th and early 20th centuries, some direct calorimeters were outfitted with equipment to measure gas exchange simultaneously with the measurement of heat. These “respiration calorimeters” were used to deduce the ratios of gas exchange to heat production and to prove the equivalence of the 2 processes—the measurement of gas exchange was shown to be an indirect but accurate reflection of energy expenditure.5 Ignoring the energy loss from urea excretion in urine was found not to significantly alter the accuracy of the IC measurement;6 for this reason, urine is usually not collected when IC is conducted.

Indirect calorimeters have many advantages over direct calorimeters in terms of smaller size, lower cost, easier measurement and maintenance, shorter measurement periods, and minimal interruption of patient care. Subjects do not need to be isolated inside of room-size chambers as long as their respiratory gases can be completely captured for approximately 30 minutes. IC is now considered a gold standard method for measuring RMR in research and clinical settings, even in critically ill patients not breathing atmospheric air. Numerous brands of IC devices are commercially available. Most consist of sensors for measuring oxygen and CO_2 concentrations in inspired and expired air, a device for measuring exhaled minute volume, and a computer system to calculate parameters and manage data.5

Ventilator-Derived Measurement of Carbon Dioxide Production

Stapel et al39 have described a method for calculating the volume of CO_2 production (VCO_2) from the end tidal CO_2 and expired gas volumes measured by some commercially available mechanical ventilators. VCO_2 is calculated as the breath-by-breath exhaled volume multiplied by the fraction of expired CO_2, averaged over a minute, and then aggregated to a 24-hour period. The theoretical respiratory quotient (RQ) of the macronutrient intake is then calculated from the actual fuel intake (or assumed to be approximately 0.85). Oxygen consumption (VO_2) is calculated from the algebraic manipulation of the RQ equation and combined with the Weir equation to calculate RMR, as follows:6

$$VO_2 = VCO_2/RQ$$

$$RMR = (VO_2 \times 3.91) + (VCO_2 \times 1.1) + 1.44$$

where RMR is measured in kcal/d, and VO_2 and VCO_2 are measured in mL/min.

Two advantages of this system are that (1) the monitoring is continuous and results in a measure of TEE rather than RMR, and (2) facilities do not need to purchase a separate indirect calorimeter. However, the functionality is probably not included in the ventilator’s basic software package and thus would need to be purchased separately. The idea of measuring just VCO_2 and calculating VO_2 and RMR by assuming an RQ is not new.5 Harris and Benedict relate a similar method in their classic monograph (measuring VCO_2 and assuming an RQ to calculate RMR).40

Reverse Fick Equation

Oxygen consumption can be estimated using the Fick principles derived from oxygen content differences in arterial and mixed venous blood multiplied by cardiac output measurements from pulmonary artery catheters.41 Placement of a pulmonary artery catheter is highly invasive, and the oxygen consumption measurements are poorly correlated with IC oxygen consumption ($R^2 = 0.30$) and biased toward underestimation.42 Therefore, the Fick equation is not useful for clinical assessment of energy expenditure.

Doubly Labeled Water

The doubly labeled water technique is another option for assessing energy expenditure. This method administers a stable isotope of water (^2H_2O) to the patient and measures its disappearance rate over time (days).[43] Disappearance of ^2H is proportional to water turnover, whereas the disappearance of ^{18}O is proportional to water turnover plus VCO_2 production. The difference between the 2 disappearance rates is the VCO_2. VO_2 is not measured; instead, it is computed from the "food quotient" (FQ), which is the sum of the CO_2 produced from all food eaten divided by the sum of the oxygen consumed during oxidation of all food eaten. From FQ and measured VCO_2, VO_2 can be computed: $VCO_2/FQ = VO_2$. Alternately, an RQ can be assumed and VO_2 computed as $VCO_2/RQ = VO_2$. The doubly labeled water technique of measuring metabolic rate is useful in field research, but it is not generally used in clinical care.

Mathematical Equations

Given the significant cost and limited availability of measurement equipment, the predominant method of determining RMR in nutrition support patients is calculation.[4,16] Many equations exist for this purpose. Not all have been tested for validity, and few of those that have been tested are considered accurate enough for general use.[44] Even the accurate equations have a significant error rate and magnitude. Most equations take advantage of correlations between body size and composition and energy use to determine RMR. Some calculation methods for sick or injured patients use an equation for healthy people multiplied by various stress factors, which are based on the type of illness or injury.[3,44] Other equations are specific to patients with illnesses or injuries and use body size and physiological variables such as body temperature, heart rate, respiratory rate, or minute volume to capture the hypermetabolism that often occurs in patients.[3,44]

Application of Methods to Determine Energy Requirements

Indirect Calorimetry

When operating an indirect calorimeter, the fundamental concept to bear in mind is that it provides a respiratory measurement and certain conditions must prevail for the respiratory measurement of gas exchange to be equivalent to metabolic gas exchange. The best way to ensure such conditions is to follow an evidence-based protocol as strictly as possible.[2,3,16] These protocols indicate that to conduct a useful IC measurement, the clinician must pay attention to the selection and preparation of the patient and environment; the measurement must meet certain quality criteria; and the overall situation of the patient and the overall care plan must be kept in mind when results are interpreted.[2,3,16]

Indications for Indirect Calorimetry

There is no absolute indication for IC. All indications are relative. For example, it has been demonstrated that the metabolic rate of an underweight critically ill or acutely ill patient is more likely to be inaccurately predicted than the metabolic rate of a normal weight or obese patient.[8] Therefore, it would seem reasonable that a low BMI is a good indication for measurement of the energy expenditure.

However, predictive energy equations are accurate about 50% of the time in underweight patients; therefore, if such a patient is receiving a calculated energy load that does not seem to be causing respiratory distress or further weight loss, then an IC measurement may not be needed. The decision to measure expenditure will nearly always be subjective, must be based on individual circumstances, and ideally is a decision of a multidisciplinary team (physician, dietitian, respiratory therapist, and nurse). Table 2-2 lists selected relative indications for IC.

TABLE 2-2 Relative Indications for Indirect Calorimetry

- Body mass index <20.5
- Body mass index >80
- Concern about overfeeding in a patient with unexplained high ventilator requirement or who for an unknown reason cannot be liberated from the ventilator
- Unwanted weight loss over time not explained by volume status in a patient who regularly receives nearly 100% of target feeding
- Massive tissue loss from amputation
- Preadmission fluid overload (ascites, volume resuscitation, “third spacing”) without a reliable report of body weight at proper hydration

Contraindications for Indirect Calorimetry

There are several absolute contraindications for IC. Again, recalling that IC is a respiratory measurement that under proper conditions is equivalent to metabolism, any factor that violates these conditions is a contraindication to IC (Table 2-3).16 Furthermore, if RMR is the desired value to be measured (and it usually is), then any factor that prevents the patient from being at rest or cooperating with the device operator is also a contraindication.

TABLE 2-3 Contraindications for Indirect Calorimetry

- Air leak (chest tubes, cuff leak, any other leak in ventilator circuit, leaks around face masks, canopies, etc)
- Extracorporeal membrane oxygenation
- Hemodialysis (during and for several hours afterward)
- For mechanically ventilated patients, a fraction of inspired oxygen >60%
- For spontaneously breathing patients:
  - Reliance on any supplemental oxygen (cannula, face mask, etc)
  - Inability to cooperate with the measurement
  - Claustrophobia or any anxiety about the measurement

Patient Preparation

Before IC is used, mechanically ventilated patients must be checked for recent ventilator changes (within the past 30 minutes)16,28 and recent nursing care involving patient movement or pain (within the past 30 minutes).28 For spontaneously breathing patients, the operator needs to check that the patient is not claustrophobic and does not have other anxiety about the measurement, that there is no supplemental oxygen in use, and that the patient has not been out of bed or received care in the past 30 minutes.

In healthy people, the definition of a resting state includes fasting. In patients who are being continuously fed by nonvolitional means, the fasting requirement is suspended, partly because it is more accurate to capture the effect,3,16 but also because it is unclear if a thermogenic effect is even present.23,24 For patients eating food by mouth, IC should be conducted after a 7-hour fast,2 and for ill patients being bolus fed, IC should not be conducted until 4 hours after the feeding.2

Environmental Factors

Although there are scant data to support the concept, it is logical that external stimulation of the patient should be minimal if RMR is to be measured.2,3,16 For example, patients should avoid reading,45 conversation, administration of care, and stimulation by family members before and during the test. Generally, the level of ambient light is reduced, although the level of light has not been proven to affect results. Ambient noise should probably be kept to a minimum—music increases RMR in conscious patients.45 In patients who are heavily sedated, comatose, or medically paralyzed, these precautions are probably less important than for a patient who is fully aware of his/her surroundings. Nursing care can increase RMR;25–28 therefore, patients should not be measured within about 30 minutes of such activities. It is not known if 30 minutes of rest time is necessary in heavily sedated critically ill patients.3

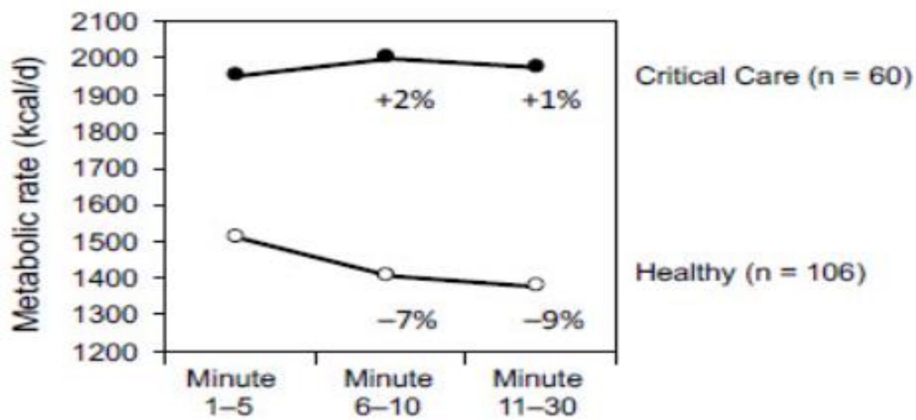
Room temperature should be controlled to the extent possible. At low ambient temperature (less than 20 degrees Celsius [68 degrees Fahrenheit]), the body will make adaptations to minimize heat loss (vasoconstriction) and increase heat production (shivering and nonshivering thermogenesis) to maintain body temperature.2,3,16 The result is an increase in metabolic rate.46–48 If the room temperature cannot be increased, use of blankets to raise the temperature of the air immediately around the patient will prevent these metabolic adaptations.46 At ambient temperature greater than body temperature, the body will give off heat to the environment to keep itself cool, thus increasing metabolic rate.49

Measurement Procedure

If all environmental and patient conditions are met, the IC measurement can be started. The step-by-step measurement procedure varies from device to device. The procedure instructions from the manufacturer should be scrupulously followed every time the indirect calorimeter is used. In addition to device configuration, these instructions include proper warm-up time and calibration of the device instruments for measuring gas volumes and concentrations.

Measurement times can vary between 10 and 30 minutes.2,3,16 The first 5 minutes of measurement are typically discarded as a time for the patient to become acclimated to the procedure. Discarding these early data is vital in conscious patients who are aware that a measurement is being conducted, and especially in patients being measured with canopy or facemask air collection systems, but it is probably not as important for sedated patients in whom the device connections are made at the ventilator rather than the nose or mouth (Figure 2-1). A period of steady state is then sought as a precaution against respiratory artifact destroying the correlation between respiratory and metabolic gas exchange. Various steady-state definitions have been validated.2,16 Most require some limit in the minute-to-minute variation in VO2 and VCO2 over a defined time period (eg, 10% coefficient of variation over 10 minutes of measurement).

FIGURE 2-1 Measurement Times for Indirect Calorimetry



Change in metabolic rate recording in the first 5-minute “discard” period in a group of critically ill, mechanically ventilated patients (closed circles) and a group of spontaneously breathing healthy volunteers (open circles). The difference between the first 5 minutes and the remainder of the test is minimal for the critically ill group but significantly different for the healthy group. Therefore, discarding the first 5 minutes of test results is important for measurements of spontaneously breathing people being measured with indirect calorimetry, but may be less so for mechanically ventilated patients. Source: Data collected by author.

Measurement Interpretation

When interpreting data, the first steps are to note whether resting conditions prevailed during the measurement and whether a steady-state period was achieved. If these conditions were met, then the 2 measured gas parameters, VO2 and VCO2, are used to calculate the metabolic rate using the modified Weir equation:6

$$RMR = [(VO2 \times 3.94) + (VCO2 \times 1.11)] \times 1.44$$

where RMR is measured in kcal/d and VO2 and VCO2 are measured in mL/min.

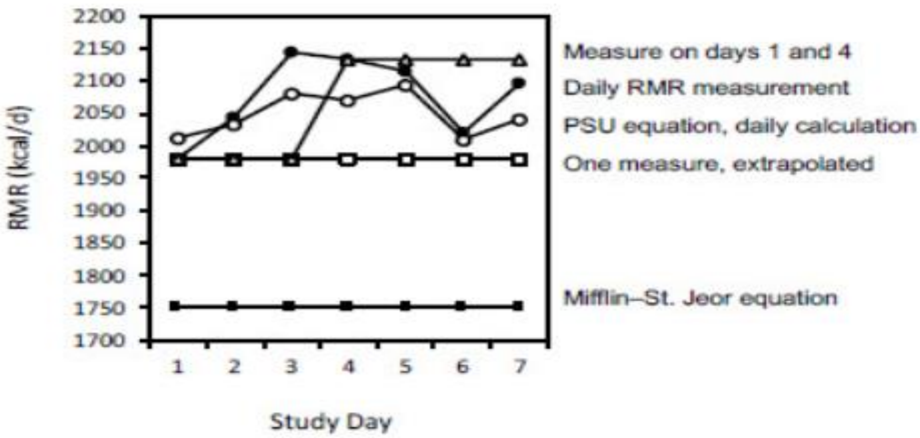
The modified version of the Weir equation differs from the full equation in that it ignores the small energy loss in the form of urea excretion. Although a small error (1% to 2%) results from this omission, using the modification means urea nitrogen does not need to be measured to complete the IC study.

RQ can be calculated as the ratio of VCO2 to VO2. The metabolic range of RQ is somewhere between 0.67 and 1.3. Although each macronutrient fuel has its own RQ signature when oxidized in isolation (eg, in a bomb calorimeter), the macronutrients are oxidized simultaneously in a living system, making interpretation of the RQ much less straightforward. The metabolic interpretation of RQ greater than 1 is net fat synthesis and is often taken as an indicator of overfeeding. However, published reports have noted RQ values greater than 1 in patients who were not being overfed and RQ less than 1 in patients who were being overfed.2,16 What then is the proper interpretation of RQ? Brandi50 wrote a remarkable paper on the effect of respiratory artifact on gas exchange measures. He produced a wide excursion in RQ by introducing respiratory artifact (creating a large and not physiological 35% change in minute ventilation by increasing or decreasing the tidal volume in patients whose clinical condition did not call for such a change). Importantly, this artificial change in minute ventilation did not significantly alter VO2 or RMR (about 2%), but it did change the apparent VCO2 (about 12%) and therefore RQ (about 16%). Thus, it is possible to produce a valid measure of RMR even when RQ and VCO2 recordings are altered by respiratory rather than metabolic factors. Clearly, a metabolic interpretation of RQ in mechanically ventilated patients can therefore be unreliable, and RQ should not be used to assess the feeding state of individual patients. The main use of RQ should be to determine whether egregious error might be present, especially if the RQ is outside the physiological range of 0.67 to 1.3. Notably, the large respiratory artifact made by Brandi50 increased the RQ to 1.02 or decreased it to 0.73 from a baseline of 0.88—changes within the physiological range.

Measurement Frequency

IC measurements in critically ill, mechanically ventilated patients have a useful life of 3 or 4 days, after which the measurement needs to be repeated or calculation methods substituted.51 IC studies repeated weekly are no more accurate over time than predictive equations (Figure 2-2).51 The necessary frequency of measurement for acutely ill spontaneously breathing patients is not known.

FIGURE 2-2 Accuracy Over Time for Measured and Calculated Resting Metabolic Rate



Cumulative measured resting metabolic rate (RMR) was 14,548 ± 2,344 kcal/d. Penn State (PSU) equation recalculated daily was 1.7% ± 5.9% below cumulative daily measurement and was more accurate than a single measurement extrapolated over the 7 days (4.1% ± 11.2% below cumulative daily measurement). Measurements conducted every 3 or 4 days are more accurate than the PSU equation (0.5% ± 4.8% above cumulative daily measurement).Source: Data collected by author, based on reference 51.

Predictive Energy Expenditure Equations for Healthy Individuals

In most instances when a nutrition support regimen is being formulated, measured RMR is not available and the clinician must rely on an estimate of the energy requirement. Equations for predicting RMR have been available since at least 1916.52 The original purpose of the equations was to develop a standard against which to test whether an RMR measurement fell within the normal range (analogous to determining the laboratory standard for serum sodium concentration in a human being). Over the decades, standard calculations have proliferated and their use has evolved to their current purpose of calculating energy prescriptions.

Harris-Benedict Equation

In 1916, Dubois may have produced the first standard metabolic equations.52 These formulas predate the now more famous Harris-Benedict equation41 by 3 years but have almost been forgotten. The Harris-Benedict equation has now also mostly transitioned from a clinical tool to a historical landmark. This equation is remarkable for 3 reasons. First is its longevity, being published in 1919. Second, it represents the first use of regression techniques in physiology.53 Third, after being initially received with some skepticism, it established linear rather than allometric scaling for calculating resting metabolism, although the argument over which approach is best continues today.54 The term allometric describes a change in one biological parameter that is not linear with another (eg, a curve).

Benedict himself recognized that the Harris-Benedict equation tended to overestimate the true RMR,55 and this observation has been documented in subsequent validation studies.45,56–59 A 2003 evidence review by the American Dietetic Association (ADA, now known as Academy of Nutrition and Dietetics [AND]) indicates that other equations are more reliable than the Harris-Benedict,44 and use of the Harris-Benedict equation has since waned. Notably, most of the descriptive studies of metabolism in illness have used the Harris-Benedict equation as the base calculation; therefore, most of the stress factors currently in use today likely need to be recalculated (or abandoned).

Mifflin–St. Jeor Equation

In 1990, Mifflin and colleagues published a study proposing new predictive equations for RMR.59 In this study, the investigators measured the RMR of 247 women and 251 men, ages 19 to 78 years. Roughly half of the subjects were obese, with a maximum BMI of 42. Fat-free mass was also measured and found to be the strongest single predictor of RMR (R2 = 0.64). However, the combination of body weight, height, age, and sex were found to correlate better than fat-free mass (R2 = 0.71), and, being easier quantities to obtain, this combination of factors was chosen to construct the predictive equation. In this way, the Mifflin–St. Jeor equation resembles the Harris-Benedict equation. Mifflin and associates obtained the highest correlation when the obese and nonobese subjects were combined into a single sex-specific equation, as follows:

Men: $RMR = 5 + (10 \times W) + (6.25 \times H) - (5 \times A)$

Women: $RMR = -161 + (10 \times W) + (6.25 \times H) - (5 \times A)$

where RMR is measured in kcal/d; W is weight (kg); H is height (cm); and A is age (years).

Whether the combining of obese and nonobese people into one equation is successful because of a statistical artifact (ie, error spread over a wider range of measured values will raise the correlation coefficient) or because it fits physiological reality is debatable, but the Mifflin–St. Jeor equation has been shown to be valid in both men and women, including people with BMI greater than the BMI in the original sample (42).38,60 The ADA systematic review found more favorable evidence for the Mifflin–St. Jeor equation than for any other,44 although the accuracy rate of Mifflin–St. Jeor falls somewhat when applied to obese people (75% in people with BMI 30 or higher compared with 87% in people with BMI less than 30) and not every study shows the Mifflin–St. Jeor equation to be the most accurate.60–62 Because of this evidence analysis, the AND recommends the Mifflin–St. Jeor equation in the current edition of Nutrition Care Manual.63

Livingston Equation

Livingston and Kohlstadt54 resurrected the linear vs allometric scaling argument with the publication of a new predictive equation in 2005. This equation was calculated from a database of the Harris-Benedict data, the Owen data,57,58 and the authors' measurements from 327 additional patients (total N = 670). The equations are simplified in that they use only weight and age, but the computation is made slightly more complex by the presence of a power function:

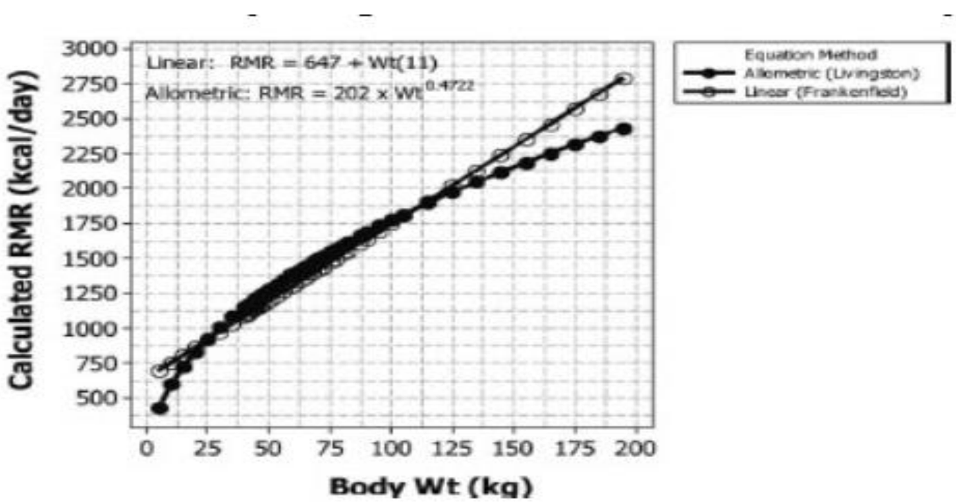
Men: RMR = (293 × W0.4330) – (5.92 × A)

Women: RMR = (248 × W0.4356) – (5.09 × A)

where RMR is measured in kcal/d; W is weight (kg); and A is age (years).

Livingston and Kohlstadt54 included a validation sample of 767 individual RMR determinations obtained from the Institute of Medicine. This validation study indicated that the Livingston and Mifflin–St. Jeor equations performed about the same in a mixed sample of obese and nonobese individuals. Weijs60 found the same result, with the Livingston and Mifflin–St. Jeor equations both accurately predicting RMR in 79% of a sample of overweight and obese Americans. (Interestingly, these equations were not as successful at predicting RMR in a sample overweight and obese Dutch.60) Frankenfield38 found the Livingston and Mifflin–St. Jeor equations predicted RMR with similar accuracy in nonobese people (88% vs 87%) but that Mifflin–St. Jeor was more accurate in obesity (75% vs 69%), including the most severely obese population (68% vs 57% accuracy) in which a curve should have been most advantageous. The allometric scaling of the Livingston equation may have been to slight advantage in people with BMI less than 20 (85% vs 80% accuracy), again in a range of BMI where a curve should be advantageous (Figure 2-3).54,64,65

FIGURE 2-3 Difference in the Relationship Between Metabolic Rate and Body Weight When Scaled Allometrically vs Linearly



The difference is small enough that the allometric scale nearly matches the linear between body weights of 25 and 150 kg. RMR, resting metabolic rate; Wt, weight. Source: Allometric equation published in Livingston and Kohlstadt.54 Linear equation based on data from Frankenfield et al.64 Reprinted with permission from reference 65: Frankenfield DC, Ashcraft CM. Estimating energy needs in nutrition support patients. JPEN J Parenter Enteral Nutr. 2011;35:563–570.

Predictive Equations for Critically Ill Patients

The 2 earliest and possibly still most common ways to predict RMR in critically ill patients are to use a ratio of kcal to kg of body weight or to calculate healthy RMR (with Harris-Benedict or Mifflin–St. Jeor) and multiply by a stress factor. The kcal/kg method continues to be promulgated by organizations such as ASPEN.1 Other organizations such as AND have recommended population-specific regression equations, such as the Penn State equations, based on the strength of evidence analysis.66

Ratio Method

The kcal/kg ratio calculation has simplicity in its favor, but it is not an accurate way to predict RMR in the critically ill. Part of this inaccuracy stems from the very simplicity of the method, which does not consider the effect of age or sex on the RMR and does not account for variation due to altered physiology, except in a subjective way—the clinician can select a kcal/kg ratio from a range of values, but there is no basis for making the selection. The effect of obesity is captured in the ASPEN method1 by changing the kcal/kg range or the mass used for the calculation (ideal body weight, rather than actual body weight, is used for patients with BMI greater than 50). Validation studies of kcal/kg ratio calculations usually show an accuracy rate of less than 50%.44

Ireton-Jones Equation

The Ireton-Jones equation was one of the first to approach metabolic rate prediction in the critically ill without adding a stress factor to a healthy RMR equation. However, the calculation uses static and categorical variables and so cannot account for dynamic changes in RMR:67 The equation is as follows:

$$RMR = 1784 - (11 \times A) + (5 \times W) + (244 \times S) + (239 \times T) + (804 \times B)$$

where RMR is measured in kcal/d; A is age (years); W is actual body weight (kg); S is sex (male = 1, female = 0); T is diagnosis of trauma (present = 1, absent = 0); and B is diagnosis of burn (present = 1, absent = 0).

Validation studies have shown that this equation has a low accuracy rate in mechanically ventilated, critical care patients.7,68–70 The AND Evidence Analysis Library for critical care nutrition does not recommend the use of the Ireton-Jones equation.3

Swinamer Equation

The Swinamer equation68 is an early example of an equation that used dynamic physiological variables in addition to body size to predict RMR in critically ill patients. The advantage of using such variables as body temperature, respiratory rate, and tidal volume is that, as these variables change from day to day, they can reflect day-to-day changes in RMR that equations based on static variables cannot. The Swinamer equation is as follows:

RMR = (BSA × 941) – (A × 6.3) + (Temp × 104) + (RR × 24) + (VT × 804) – 4243

where RMR is measured in kcal/d; BSA is body surface area (m2); A is age (years); Temp is body temperature (degrees Celsius); RR is respiratory rate (breaths/min); and VT is tidal volume (L).

The Swinamer equation has been found to accurately predict RMR in about 55% of patients and to cause large error (more than 15% above measured RMR) 30% of the time.7 In the AND systematic review, the equation was not recommended for use because of this high error rate.3

Penn State Equation

The Penn State equation was first published in 1998 and revised twice based on subsequent validation studies.71 Like the Swinamer equation, it combines variables that relate RMR to body size and composition (ie, the Mifflin–St. Jeor equation) with dynamic physiological variables to capture day-to-day variation in the RMR. The Penn State equation is as follows:72

RMR = (Mifflin–St. Jeor × 0.96) + (VE × 32) + (Tmax × 167) – 6212

where RMR and Mifflin–St. Jeor estimates are measured in kcal/d; Tmax is maximum body temperature in the previous 24 hours (degrees Celsius); and VE is minute ventilation (L/min).

Numerous validation studies have been conducted on this equation,7,8,24,51,73–78 and it has been recommended for use by AND.3 Since the AND recommendation was made, the equation has been demonstrated to be accurate in morbidly obese patients (80% accuracy up to a BMI of at least 80), patients with brain injuries (72% accuracy), and patients in barbiturate coma (73% accuracy). Accuracy rates are lower in patients with low BMI (63% accuracy when BMI is less than 20.5) and patients with cystic fibrosis (58% accuracy; most of these patients had very low BMI, which might be the underlying reason for the low accuracy rate). In a study of serial RMR measurements, the equation was more accurate if recalculated daily than a single RMR measurement extrapolated for 7 days. Measurement of RMR was more accurate than the equation only when measurement was repeated every 3 or 4 days.51 (See Figure 2-2.)

Not all research studies show the Penn State equation to be valid. In a study by De Waele and associates,76 correlation between measured RMR and the Penn State equation was low; also, the mean difference between the 2 values (–265 kcal); and the limit of agreement (–872 to 340 kcal/d) were both large. The study did not report the accuracy rate. Two cautionary aspects of this study are worthy of mention because they could explain the result. The first is that the measured RMR seems low (1571 ± 424 kcal/d or 8% above the calculated Mifflin–St. Jeor value),76 compared with the original Penn State equation validation work (2000 ± 534 kcal/d or 23% above calculated Mifflin–St. Jeor),7 but the indirect calorimeter used in the De Waele study (the Vmax Encore) tends to measure RMR lower than the Deltatrac (the device used in the original Penn State equation work).79 The second is that the Penn State equation value may have been miscalculated in the De Waele study. Based on reported mean height, weight, age, sex, body temperature, and minute ventilation, the mean Penn State equation value should have been 1697 kcal/d rather than the reported 2106 kcal/d. Considering both of these factors together, it is possible that the RMR measurement should have been higher and the RMR estimate should have been lower in the De Waele study, resulting in better agreement with the Penn State calculations than was reported.

Ratzlaff and colleagues tested the Penn State equation for validity in mechanically ventilated cardiothoracic surgery patients and reported the equation accuracy to be 11% compared with measured RMR.77 Insufficient descriptive data were included in the paper to recreate the Penn State equation calculation; however, given that this was a retrospective study, it is possible that the incorrect body weight, body temperature, or minute ventilation was used in the computation. The measured RMR in this study is a greater concern. The mean RMR was 2406 ± 587 kcal/d, and the device used was the Medgraphics Ultima.77 Sundstrom et al80 have shown that measurements from the Medgraphics Express, a similar device from the same manufacturer and using similar, if not the same, technology, differed markedly from Deltatrac measurements in the same patients (2876 ± 656 kcal/d vs 1749 ± 389 kcal/d). As stated previously, the Deltatrac was the device used in the original Penn State equation work. It is therefore quite possible that the IC data were out of phase in the Ratzlaff study.73 By comparison to the 2406 kcal/d value recorded, measured RMR in the other validation studies of the Penn State equation were 2000 kcal/d,7 1571 kcal/d,76 and 2029 kcal/d.78

In a third study in which the Penn State equation (and numerous other predictive equations) failed to predict RMR, de Góes and associates measured RMR in critically ill patients with acute kidney injury using a Quark RMR indirect calorimeter.78 Measurements were conducted before renal replacement therapy was initiated, and measured RMR was similar to the Penn State equation validation study7 but with a higher standard deviation (2029 ± 760 kcal/d vs 2000 ± 533 kcal/d). Nine equations were tested. Of these 9, 8 were also tested by Frankenfield and colleagues in 2009.7 In every equation except 1, the accuracy rate was higher in the Frankenfield paper. For example, the Penn State equation accuracy was 33% in de Góes vs 67% in Frankenfield, and the accuracy rates for the Ireton-Jones equation were 27% and 46%, respectively.7,78 Possible reasons for the discrepancies between the 2 studies include differences in the equipment used and the types of patients studied. In 2013, Sundstrom and coauthors found the Quark RMR device used in the de Góes study to be accurate;80 however, in subsequent work (2016), Sundstrom et al noted a bias of about 10%, with a tendency for the Quark to measure higher than the Deltatrac.81 Patients in the study by de Góes et al had acute kidney injury, and their pulmonary gas exchange values therefore may not have fully represented metabolic gas exchange. More importantly, the de Góes paper originated in Brazil, and it may be that the base RMR in this population is poorly represented by the Mifflin–St. Jeor equation, which, if true, would make the Penn State equation also inaccurate.62 The Mifflin–St. Jeor equation underestimated RMR by a mean of 14% in healthy Brazilians, and the Penn State equation, which uses the Mifflin–St. Jeor equation, underestimated RMR by a mean of 5% in critically ill Brazilians.62

Predictive Equations for Acutely Ill Patients

Much research has been focused on describing and predicting the RMR of mechanically ventilated, critically ill patients. However, this research cannot necessarily be used to guide energy assessment in nutrition support patients who are spontaneously breathing. Certainly, any equation that contains minute ventilation or tidal volume as a variable cannot be used in these patients because those variables are not measured. Two equations have been proposed for spontaneously breathing, acutely ill patients, and these equations have recently undergone validation testing. The first of these equations is from Ireton-Jones:67

$$RMR = (W \times 25) - (A \times 11) - (OB \times 609) + 629$$

where RMR is measured in kcal/d; W is actual weight (kg); A is age (years); and OB is presence of obesity (1 = yes; 0 = no).

The second equation is from Frankenfield and Ashcraft and is based on the validation data for the Penn State equation absent the minute ventilation variable:65

$$RMR = (\text{Mifflin–St. Jeor} \times 0.94) + (T_{max} \times 186) - 6597$$

where RMR is measured in kcal/d; Mifflin–St. Jeor (kcal/d) is calculated using actual body weight; and Tmax is maximum body temperature in the previous 24 hours (degrees Celsius).

These equations were tested in a group of 55 acutely ill, spontaneously breathing hospitalized patients receiving nutrition support.35 The modified Penn State equation was accurate 71% of the time compared with 44% of the time for the Ireton-Jones equation. Similar to the Penn State equation for mechanically ventilated, critically ill patients, the predictions using the Penn State equation for spontaneously breathing patients failed more often in underweight patients (accuracy rate 47%) than in normal weight (76% accuracy rate) or obese patients (84% accuracy rate).

Measurements from Mechanical Ventilators

Stapel and coauthors39 conducted a validation study of RMR calculated from ventilator-derived VCO_2 vs IC with a Deltatrac. Several equations also were included in the validation study (Harris-Benedict, 25 kcal per kg body weight, Faisy, and Penn State). Two error thresholds were evaluated. The VCO_2 method was accurate to within 10% of measured values in 61% of patients compared with 40% for the ratio method and 54% for the Penn State equation. For a 15% error threshold, the VCO_2 method was accurate 79% of the time, the ratio method 56% of the time, and the Penn State equation 75% of the time.

Nutrition Support Therapy and Energy Requirements

The human body requires a constant supply of energy to maintain homeostasis. If this energy is not supplied by food, the body must catabolize itself to meet the deficit. The body can do this for a time without suffering impairment, but function will eventually be compromised by the resulting tissue loss. The length of time before compromise depends on the patient's nutrition status, the size of the energy deficit, and the body compartment being catabolized. The critical deficit may be reached sooner in (1) malnourished patients (because they start with a reduced tissue reserve), (2) hypermetabolic patients (because they create larger daily deficits), and (3) in cases where inflammatory response favors catabolism of protein over fat. One of the goals of nutrition support is to minimize this energy deficit while avoiding overfeeding. The degree of precision required for the energy prescription is still debated by researchers and practicing clinicians. However, in general, an accurate assessment of energy demand is an important part of the nutrition care of the patient receiving nutrition support. Practice Scenario 2-1 addresses several questions related to energy assessment in a critically ill, obese, older man receiving nutrition support.1,82

Practice Scenario 2-1

Scenario: A 73-year-old man was admitted to the critical care unit with respiratory failure related to pneumonia. The condition progressed to acute respiratory distress syndrome, and the patient was also in septic shock. He had a spontaneous pneumothorax for which he received a chest tube, which developed an air leak. His previous medical history included diabetes mellitus and congestive heart failure. Since he was intubated and expected to remain so for at least 3 days, a feeding tube was placed, a low-rate tube feeding was started, and a nutrition support consult was ordered.

When reviewing the chart, the dietitian noted a current body weight of 165 kg and a height of 178 cm, which would suggest the body mass index (BMI) to be 52.1. However, intake/output records indicated a large volume resuscitation for the septic shock, and the physician note indicated +4 edema in all extremities. Clearly, the current body weight of 165 kg was skewed by volume overload. Fortunately, the patient had been followed in one of the hospital clinics for his chronic conditions, which meant that his electronic health record contained a preadmission history of measured body weights. This record indicated that his body weight fluctuated due to water retention from his congestive heart failure, but the nadir was 120 kg for a BMI of 37.9. The dietitian went to the bedside and observed that the recorded height of 178 cm seems to be accurate. The dietitian also observed obvious edema, as noted by the physician, which explained the discrepancy in body weight between the value recorded in clinic and the value recorded in the critical care unit. Therefore, 120 kg and 178 cm were taken as the patient's true weight and height. His Nutrition Risk Screening score was 4 (0 points for nutrition, 3 points for disease state, 1 point for age).82 Current vital signs were maximum body temperature 37.8 degrees Celsius, heart rate 110 beats/min, and minute ventilation 11.5 L/min. His fraction of inspired oxygen was 70%, and his arterial blood gas was 7.33/50/90/33 (respiratory acidosis not yet compensated). He was sedated with fentanyl and receiving norepinephrine to support his blood pressure.

Question 1: Should indirect calorimetry (IC) be used in this scenario? Why or why not?

Answer 1: In this case, fluid overload masked the patient's true body weight. The rationale for measuring resting metabolic rate (RMR) with IC would be that current body weight was grossly different from his dry weight, which would interfere with calculating the RMR. However, the dietitian had a way of determining the dry weight. The patient had severe obesity but his dry weight and BMI were not in the range that would categorically invalidate prediction equations for his RMR. Therefore, there would be no strict indication to conduct an IC measurement.

Question 2: Would IC be feasible for this patient?

Answer 2: No. The patient had an air leak from his chest tube and his fraction of inspired oxygen was too high for an open-circuit indirect calorimeter to function accurately.

Question 3: What body weight should be used for calculating RMR? What values would result?

Answer 3: Current BMI was greater than 50, and the American Society for Parenteral and Enteral Nutrition (ASPEN) guidelines1 suggest using ideal body weight for RMR calculation in this weight class. However, his dry weight BMI was 37.9; therefore, actual body weight would be used. The ASPEN guidelines1 suggest 11 to 14 kcal per kg body weight, which would mean his calculated RMR would be 1320 to 1680 kcal/d. The Penn State equation result would be 2335 kcal/d. One reason for the discrepancy between the 2 values is that the ASPEN standard is modified to represent 65% to 70% of the theoretical true RMR if measured with IC.

Question 4: Two weeks later, the patient remained on the ventilator despite attempts to liberate him from it. Fraction of inspired oxygen decreased to 50%, and the chest tube had been removed. His minute ventilation was unexpectedly high (20.3 L/min). He was febrile (body temperature 38.5 degrees Celsius), and his body weight was 125 kg. The dietitian had set the energy intake goal at 2725 kcal/d, but the critical care team wondered whether overfeeding might explain his high minute ventilation. Would IC now be appropriate?

Answer 4: At this point, IC would be more clearly indicated. The critical care team had no explanation for his elevated minute ventilation and failure to wean from the ventilator. Although his current body weight was now close to his usual dry weight, it was likely that the patient lost tissue mass during his past 2 weeks of illness so that his new true dry body weight could be below his baseline weight of 120 kg. If the estimate of dry body weight were too high, the Penn State equation would overestimate his energy demand, leading to overfeeding. Measurement of his RMR would quickly determine whether his RMR were lower than expected. The IC data could furthermore be used to determine dead space ventilation, which could help the team determine why his minute ventilation was so high.

Question 5: The patient's IC results were RMR 2500 kcal/d, respiratory quotient 0.84, oxygen consumption 370 mL/min, volume of carbon dioxide production (VCO_2) 302 mL/min, and minute ventilation 20.1 L/minute. The arterial blood gas was 7.36/50/120/40 (compensated respiratory acidosis). Analyze and interpret these data.

Answer 5: The measured RMR was11% lower than the predicted RMR, which indicates that the patient was being slightly overfed. The degree of overfeeding would not likely be the cause for the patient's continued ventilator dependence or high minute ventilation.

With the available data, the patient's dead space fraction (Vd/Vt) could be calculated. He had a partial pressure of carbon dioxide ($PaCO_2$) of 50 torr and a mixed expiratory CO_2 ($FeCO_2$) concentration of 1.50% calculated from the IC data. Barometric pressure read from the indirect calorimeter was 747 mmHg, and the pressure of water vapor was assumed to be 47 mmHg. Therefore, his partial pressure of mixed expiratory carbon dioxide ($PeCO_2$) was 9.8 torr, and his dead space fraction was 80%. The mathematical steps for this calculation are as follows:

$FeCO_2 = VCO_2/Ve = (302/20100) = 0.0150$

$PeCO_2 = (\text{Barometric Pressure} – 47) \times FECO_2 = (747 – 47) \times 0.0150) = 9.8$

$Vd/Vt = (PaCO_2 – PeCO_2)/PaCO_2 = (50 – 9.8)/50 = 0.80$

where VCO_2 is volume of CO_2 production (mL/min); Ve is expired volume (mL/min); and $PeCO_2$ is measured in torr.

Even in the absence of an arterial blood gas, his ventilatory equivalent (Ve/VCO_2, the liters of minute volume required to remove 1 liter of carbon dioxide) was high (66.6 L/L), indicating that his problem was not metabolic in nature.

Question 6: Eventually, the patient was liberated from the ventilator. He was not cleared by the speech pathologist to start an oral diet, so he remained on tube feeding. His body weight decreased to 110 kg, there was no sign of edema, and he was up and walking frequently. Maximum body temperature was 36.5 degrees Celsius. At this point, what would be his energy requirement?

Answer 6: The patient's Mifflin–St. Jeor equation value was 1850 kcal/d at his new dry weight, and his RMR calculated by the Penn State equation for spontaneously breathing people was 1930 kcal. This RMR was only 4% above his Mifflin–St. Jeor value, indicating that the patient was no longer hypermetabolic. There was probably no thermogenic effect of feeding since he remained on a continuous feeding infusion; however, the energy goal might need adjustment for movement (walking) of about 10%, bringing his total energy requirement to 2125 kcal/d.