Chapter 6

Measurement of Energy in Food and During Physical Activity



Outline

Measurement of Food Energy

- The Calorie—A Unit of Energy Measurement
- Gross Energy Value of Foods
- Net Energy Value of Foods
- Energy Value of a Meal

Measurement of Human Energy Expenditure

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- Energy Expenditure During Rest and Physical Activity
- Factors Affecting Energy Expenditure
- Energy Expenditure During Physical Activity
- Average Daily Rates of Energy Expenditure
- The Metabolic Equivalent (MET)

Test Your Knowledge

Answer these 10 statements about the measurement of energy in food and during physical activity. Use the scoring key at the end of the chapter to check your results. Repeat this test after you have read the chapter and compare your results.

- 1. **T F** The calorie is a unit of energy measurement.
- 2. **T F** The bomb calorimeter operates on the principle of indirect calorimetry by measuring the oxygen consumed as the food burns completely.
- 3. **T F** Heat of combustion refers to a food's ability to release carbon dioxide in relation to oxygen consumed as it burns completely.
- 4. **T** F The heat of combustion for all carbohydrates averages 5.0 kCal per gram.
- 5. T F The heat of combustion for lipid averages 6.0 kCal per gram.
- 6. **T** F The heat of combustion for protein averages 7.0 kCal per gram.
- 7. **T F** The doubly labeled water technique provides a way to evaluate sweat loss during intense exercise.
- 8. T F In terms of net energy release in the body, each of the three macronutrients releases about 4.0 kCal per gram.
- 9. T F Celery would become a "fattening" food if consumed in excess.
- 10. T F The respiratory quotient (RQ) for carbohydrate equals 1.00.



ll biologic functions require energy. The carbohydrate, lipid, and protein macronutrients contain the energy that ultimately powers biologic work, making energy the common denominator for classifying both food and physical activity.

Measurement of Food Energy

THE CALORIE—A UNIT OF ENERGY MEASUREMENT

In nutritional terms, one calorie expresses the quantity of heat necessary to raise the temperature of 1 kg (1 L) of water 1° C (specifically, from 14.5 to 15.5°C). Thus, **kilogram calorie** or kilocalorie (**kCal**) more accurately defines calorie. (Note the use of the letter k to designate a kilocalorie, as compared to a small calorie (c) that indicates the quantity of heat necessary to raise the temperature of 1 g of water 1°C.) For example, if a particular food contains 300 kCal, then releasing the potential energy trapped within this food's chemical structure increases the temperature of 300 L of water 1°C.

Different foods contain different amounts of potential energy. One-half cup of peanut butter with a caloric value of 759 kCal contains the equivalent heat energy to increase the temperature of 759 L of water 1°C. A corresponding unit of heat using Fahrenheit degrees is the British thermal unit or BTU. One BTU represents the quantity of heat necessary to raise the temperature of 1 lb (weight) of water 1°F from 63 to 64°F. A clear distinction exists between temperature and heat. Temperature reflects a quantitative measure of an object's hotness or coldness. Heat describes energy transfer (exchange) from one body or system to another. The following conversions apply:

1 cal = 4.184 J 1 kCal = 1000 cal = 4186 J = 4.184 kJ1 PTU = 778 ft h = 252 cal = 1055 J

1 BTU = 778 ft lb = 252 cal = 1055 J

The joule, or **kilojoule** (**kJ**), reflects the standard international unit (SI unit) for expressing energy. To convert kilocalories to kilojoules, multiply the kilocalorie value by 4.184. The kilojoule value for 1/2 cup of peanut butter, for example, would equal 759 kCal \times 4.184, or 3176 kJ. The **megajoule** (**MJ**) equals 1000 kJ; its use avoids unmanageably large numbers. The name joule honors British scientist Sir Prescott Joule (1818–1889), who studied how vigorous stirring of a paddle wheel warmed water. Joule determined that the movement of the paddle wheel added energy to the water, raising the water temperature in direct proportion to the work done.

GROSS ENERGY VALUE OF FOODS

Laboratories use **bomb calorimeters** similar to one illustrated in FIGURE 6.1 to measure the total heats of combustion (see below) values of the various food macronutrients. Bomb calorimeters operate on the principle of **direct calorimetry**, measuring the heat liberated as the food burns completely.

Figure 6.1 shows food within a sealed chamber charged with oxygen at high pressure. An electrical current moving through the fuse at the tip ignites the food–oxygen mixture. As the food burns, a water jacket surrounding the bomb absorbs the heat (energy) liberated. Because the calorimeter is fully insulated from the outside environment, the increase in water temperature *directly* reflects the heat released during a food's oxidation (burning).

Heat of combustion refers to the heat liberated by oxidizing a specific food; it represents the food's total energy value. For example, a teaspoon of margarine releases 100 kCal of heat energy when burned completely in a bomb calorimeter. This equals the energy required to raise 1.0 kg (2.2 lb) ice water to its boiling point. The oxidation pathways of food in the intact organism and the bomb calorimeter differ, but the energy liberated in the complete breakdown of a food remains the same, regardless of the combustion pathways.

Carbohydrates

The heat of combustion for carbohydrate varies depending on the arrangement of atoms in the particular carbohydrate molecule. For glucose, heat of combustion equals 3.74 kCal per



FIGURE 6.1 A bomb calorimeter directly measures the energy value of food.

gram, about 12% less than for glycogen (4.19 kCal) and starch (4.20 kCal). For 1 g of carbohydrate, a value of 4.2 kCal generally represents the average heat of combustion.

Lipids

The heat of combustion for lipid varies with the structural composition of the triacylglycerol molecule's fatty acid components. For example, 1 g of either beef or pork fat yields 9.50 kCal, whereas oxidizing 1 g of butterfat liberates 9.27 kCal. The average energy value for 1 g of lipid in meat, fish, and eggs equals 9.50 kCal. In dairy products, the energy equivalent amounts to 9.25 kCal per gram, and 9.30 kCal in vegetables and fruits. *The average heat of combustion for lipid equals 9.4 kCal per gram*.

Proteins

Two factors affect energy release from protein combustion: (1) type of protein in the food and (2) relative nitrogen content of the protein. Common proteins in eggs, meat, corn (maize), and beans (jack, lima, navy, soy) contain approximately 16% nitrogen, and have a corresponding heat of combustion that averages 5.75 kCal per gram. Proteins in other foods have a somewhat higher nitrogen content; most nuts and seeds contain 18.9% nitrogen, and whole-kernel wheat, rye, millets, and barley contain 17.2%. Other foods contain a slightly lower nitrogen percentage; for example, whole milk has 15.7% and bran 15.8%. *The heat of combustion for protein averages 5.65 kCal per gram*.

Comparing Macronutrient Energy Values

The average heats of combustion for the three macronutrients (carbohydrate, 4.2 kCal \cdot g⁻¹; lipid, 9.4 kCal \cdot g⁻¹; protein, 5.65 kCal \cdot g⁻¹) demonstrates that the complete oxidation of lipid in the bomb calorimeter liberates about 65% more energy per gram than protein oxidation and 120% more energy than carbohydrate oxidation. Recall from Chapter 1 that a lipid molecule contains more hydrogen atoms than either carbohydrate or protein molecules. The common fatty acid palmitic acid, for example, has the structural formula $C_{16}H_{32}O_2$. The ratio of hydrogen atoms to oxygen atoms in fatty acids always greatly exceeds the 2:1 ratio in carbohydrates. Simply stated, lipid molecules have more hydrogen atoms available for cleavage and subsequent oxidation for energy than carbohydrates and proteins.

One can conclude from the previous discussion that lipidrich foods have a higher energy content than foods relatively fat free. One cup of whole milk contains 160 kCal, whereas the same quantity of skim milk contains only 90 kCal. If a person who normally consumes 1 quart of whole milk each day switches to skim milk, the total calories ingested each year would decrease by the equivalent calories in 25 pounds of body fat! In 3 years, all other things remaining constant, body fat loss would approximate 75 pounds. Such a theoretical comparison merits serious consideration because of the almost identical nutritional composition between whole milk and skim milk except for fat content. Drinking an 8-oz glass of skim milk rather than whole milk also significantly reduces saturated fatty acid intake (0.4 vs 5.1 g) and cholesterol (0.3 vs 33 mg).

Interchangeable Expression for Energy and Work

- 1 foot-pound (ft-lb) = 0.13825 kilogram-meters (kg-m)
- 1 kg-m = 7.233 ft-lb = 9.8066 joules
- 1 kilocalorie (kCal) = 3.0874 ft-lb = 426.85 kg-m =
- 4.186 kilojoules (kJ)
- 1 joule (J) = 1 Newton-meter (Nm)
- 1 kilojoule (kJ) = 1000 J = 0.23889 kCal

NET ENERGY VALUE OF FOODS

Differences exist in the energy value of foods when comparing the heat of combustion determined by direct calorimetry (gross energy value) to the net energy value actually available to the body. This pertains particularly to proteins, because the body cannot oxidize the nitrogen component of this nutrient. Rather, nitrogen atoms combine with hydrogen to form urea (NH₂CONH₂) for excretion in the urine. Elimination of hydrogen in this manner represents a loss of approximately 19% of the protein molecule's potential energy. This hydrogen loss reduces protein's heat of combustion in the body to approximately 4.6 kCcal per gram instead of 5.65 kCal per gram released during oxidation in the bomb calorimeter. In contrast, *identical* physiologic fuel values exist for carbohydrates and lipids (which contain no nitrogen) compared with their respective heats of combustion in the bomb calorimeter.

Coefficient of Digestibility

The efficiency of the digestive process influences the ultimate caloric yield from macronutrients. Numerically defined as the **coefficient of digestibility**, digestive efficiency represents the percentage of ingested food digested and absorbed to serve the body's metabolic needs. The food remaining unabsorbed in the intestinal tract becomes voided in the feces. Dietary fiber reduces the coefficient of digestibility: A high-fiber meal has less total energy absorbed than does a fiber-free meal of equivalent caloric content. This difference occurs because fiber moves food more rapidly through the intestine, reducing absorption time. Fiber also may cause mechanical erosion of the intestinal mucosa, which then becomes resynthesized through energy-requiring processes.

TABLE 6.1 shows different digestibility coefficients, heats of combustion, and net energy values for nutrients in the various food groups. *The relative percentage of macronutrients completely digested and absorbed averages 97% for carbohydrate, 95% for lipid, and 92% for protein.* Little difference exists in digestive efficiency between obese and lean individuals. However, considerable variability exists in efficiency percent-

ages for any food within a particular category. Proteins in particular have variable digestive efficiencies, ranging from a low of about 78% for high-fiber legumes to a high of 97% for protein from animal sources. Some advocates promote the use of vegetables in weight loss diets because of plant protein's relatively low coefficient of digestibility. Those on a vegetarian-type diet should consume adequate and diverse protein food sources to obtain all essential amino acids (see Chapter 1).

From the data in Table 6.1, the average net energy values can be rounded to simple whole numbers referred to as **Atwater general factors** (http://www.sportsci.org/news/ history/atwater/atwater.html).

Atwater General Factors

- 4 kCal per gram for carbohydrate
- 9 kCal per gram for lipid
- 4 kCal per gram for protein

These values, named for Wilbur Olin Atwater (1844–1907), the 19th-century chemist who pioneered human nutrition and energy balance studies, represent the energy available to the body from ingested foods. Except when requiring exact energy values for experimental or therapeutic diets, the Atwater general factors accurately estimate the *net metabolizable energy* of typically consumed foods. For alcohol, 7 kCal (29.4 kJ) represents each g (mL) of pure (200 proof) alcohol ingested. In terms of metabolizable energy available to the body, alcohol's efficiency of use equals that of other carbohydrates.¹⁵

ENERGY VALUE OF A MEAL

The Atwater general factors can determine the caloric content of any portion of food (or an entire meal) from the food's composition and weight. TABLE 6.2 illustrates the method for calculating the kCal value of 100 g (3.5 oz) of chocolate-chip ice cream. Based on laboratory analysis, this ice cream contains approximately 3% protein, 18% lipid, and 23% carbohydrate, with the remaining 56% being essentially water. Thus, each gram of ice cream contains 0.03 g protein, 0.18 g lipid, and 0.23 g carbohydrate. Using these compositional values and the Atwater factors, the following represents the kCal value per gram of the chocolate-chip ice cream: Net kCal values show that 0.03 g of protein contains 0.12 kCal (0.03×4.0 kCal \cdot g⁻¹), 0.18 g lipid contains 1.62 kCal (0.18 \times 9 kCal \cdot g^{-1}), and 0.23 g carbohydrate contains 0.92 kCal (0.23 \times 4.0 kCal \cdot g⁻¹). Combining the separate values for the nutrients yields a total energy value for each gram of chocolate-chip ice cream of 2.66 kCal (0.12 + 1.62 + 0.92). A 100-g serving yields a caloric value 100 times as large or 266 kCal. The percentage of total calories derived from lipid equals 60.9% (162 lipid kCal ÷ 266 total kCal). Similar computations estimate the caloric value for any food serving. Of course, increasing or decreasing portion sizes (or adding lipid-rich sauces or

TABLE 6.1 Factors for Digestibility, Heats of Combustion, and Net Physiologic Energy Values ^a of Dietary Protein, Lipid, and Carbohydrate						
Food Group	Digestibility (%)	Heat of Combustion (kCal·g ⁻¹)	Net Energy (kCal·g ⁻¹)			
Protein						
Meats, fish Eggs Dairy products <i>Animal food (Average)</i> Cereals Legumes Vegetables Fruits <i>Vegetable food (Average)</i>	97 97 97 85 78 83 83 85 85	5.65 5.75 5.65 5.65 5.80 5.70 5.00 5.20 5.65	4.27 4.37 4.27 3.87 3.47 3.11 3.36 3.74			
Total protein, Average	92	5.65	4.05			
Lipid						
Meat and eggs Dairy products Animal food Vegetable food Total lipid, Average	95 95 95 90 95	9.50 9.25 9.40 9.30 9.40	9.03 8.79 8.93 8.37 8.93			
Carbohydrate						
Animal food Cereals Legumes Vegetables Fruits Sugars	98 98 97 95 90 98	3.90 4.20 4.20 4.20 4.20 4.00 3.95	3.82 3.11 4.07 3.99 3.60 3.87			
Vegetable food Total carbohydrate, Average	97 97	4.15 4.15	4.03 4.03			

From Merrill AL, Watt BK. Energy values of foods: basis and derivation. Agricultural handbook no. 74, Washington, DC: U.S. Department of Agriculture, 1973. ^aNet physiologic energy values computed as the coefficient of digestibility times the heat of combustion adjusted for energy loss in urine.

creams or using fruits or calorie-free substitutes) affects caloric content accordingly.

Computing the caloric value of foods is time-consuming and laborious. Various governmental agencies in the United States and elsewhere have evaluated and compiled nutritive values for thousands of foods. The most comprehensive data bank resources include the U.S. Nutrient Data Bank (USNDB) maintained by the U.S. Department of Agriculture's (USDA) Consumer Nutrition Center,¹⁰ and a computerized data bank maintained by the Bureau of Nutritional Sciences of Health and Welfare Canada.⁸ Many commercial software programs make use of the original USDA nutritional databases, which are available for download to the public for a nominal fee. (The USDA Nutrient Database for Standard Reference Release 11 can be viewed or downloaded from www.nal.usda.gov/fnic/food comp/Data/SR11/ae11.html; access the Nutrient Data Laboratory at www.nal.usda.gov/fnic/foodcomp/; and access the Food and Nutrition Information Center, National Agricultural Library, Agricultural Research Service of the USDA at www.nalusda.gov/fnic/).

Appendix A presents energy and nutritive values for common foods, including specialty and fast-food items. Compute nutritive values for specialty dishes such as chicken or beef tacos from standard recipes; actual values vary considerably depending on the method of preparation. Examination of Appendix A reveals large differences among the energy values of various foods. Consuming an equal number of calories from diverse foods often requires increasing or decreasing the quantity of a particular food. For example, to consume 100 kCal from each of six common foods-carrots, celery, green peppers, grapefruit, medium-sized eggs, and mayonnaiseone must eat 5 carrots, 20 stalks of celery, 6.5 green peppers, 1 large grapefruit, 1¼ eggs, but only 1 tablespoon of mayonnaise. Consequently, an average sedentary adult woman would need to consume 420 celery stalks, 105 carrots, 136 green peppers, or 26 eggs, yet only 1½ cup of mayonnaise or 8 oz of salad oil, to meet her daily 2100-kCal energy needs. These examples dramatically illustrate that foods high in lipid content contain considerably more calories than foods low in lipid with correspondingly higher water content.

TABLE 6.2	Method for Calculating the Caloric Value of a
	Food from Its Composition of Macronutrients

Food: ice cream (chocolate with chocolate chips) Weight: $\frac{3}{2}$ cup = 100 g

AAG	igni.	74	cup	_	100	y	

	Composition						
	Protein	Lipid	Carbohydrate				
Percentage	3%	18%	23%				
Total grams	3	18	23				
In 1 g	0.03	0.18	0.23				
Calories per gram	0.12	1.62	0.92				
(0.04 $ imes$ 4.0 kCal) + (0.18 $ imes$ 9.0 kCal) + (0.23 $ imes$ 4.0 kCa							
Total calories per gram: 0.12 + 1.62 + 0.92 = 2.66 kCa							
Total calories per 100 g: 2.66 $ imes$ 100 = 266 kCal							
Percentage of calories from lipid: (18 g $ imes$ 9.0 kCal \cdot g ⁻¹)							
÷ 266 kCal = 60).9%						

Note that a calorie reflects food energy *regardless* of the food source. Thus, from a standpoint of energy, 100 kCal from mayonnaise equals the same 100 kCal in 20 celery stalks. The more one eats of any food, the more calories one consumes. However, a small quantity of fatty foods represents a considerable quantity of calories; thus, the term "fattening" often describes these foods. An individual's caloric intake equals the sum of *all* energy consumed from either small or large food portions. Indeed, celery becomes a "fattening" food if consumed in excess! Chapter 7 considers variations in daily energy intake among sedentary and active individuals, including diverse groups of athletes.

Case Study

Personal Health and Exercise Nutrition 6–1



Nutrient Timing to Optimize Muscle Response to Resistance Training

An evidence-based nutritional approach can enhance the quality of resistance training and facilitate muscle growth and strength development. This easy-to-follow new diminsion to sports nutrition emphasizes not only the specific type and mixture of nutrients but also the timing of nutrient intake. Its goal is to blunt the catabolic state (release of hormones glucagon, epinephrine norephinephrine, cortisol) and activate the natural muscle-building hormones (testosterone, growth hormone, IGF-1, insulin) to facilitate recovery from exercise and maximize muscle growth. Three phases for optimizing specific nutrient intake are proposed:

 The energy phase (1) enhances nutrient intake to spare muscle glycogen and protein, (2) enhances muscular endurance, (3) limits immune system suppression, (4) reduces muscle damage, and (5) facilitates recovery in the postexercise period. Consuming a carbohydrate/protein supplement in the immediate pre-exercise period and during exercise extends muscular endurance; the ingested protein promotes

Case Study continued

protein metabolism, thus reducing demand for muscle's release of amino acids. Carbohydrates consumed during exercise suppress cortisol release. This blunts the suppressive effects of exercise on immune system function and reduces branched-chain amino acids generated by protein breakdown for energy.

The recommended *energy phase* supplement profile contains the following nutrients: 20 to 26 g of high-glycemic carbohydrates (glcose, sucrose, maltodextrin), 5 to 6 g whey protein (rapidly digested, high-quality protein separated from milk in the cheese-making process), 1 g leucine, 30 to 120 mg vitamin C, 20 to 60 IU vitamin E, 100 to 250 mg sodium, 60 to 100 mg potassium, and 60 to 220 mg magnesium.

2. The anabolic phase consistes of the 45-minute postexercise metabolic window—a period that enhances insulin sensitivity for muscle glycogen replenishment and muscle tissue repair and synthesis. This shift from catabolic to anabolic state occurs largely by blunting the action of cortisol and increasing the anabolic, muscle-building effects of insulin by consuming a standard high-glycemic carbohydrate/protein supplement in liquid form (e.g., whey protein and high-glycemic carbohydrates). In essence, the high-glycemic carbohydrate consumed post exercise serves as a nutrient activator to stimulate insulin release, which in the presence of amino acids increases muscle tissue synthesis and decreases protein degradation.

The recommended *anabolic phase* supplement profile contains the following nutrients: 40 to 50 g of high-glycemic carbo-hydrates (glucose, sucrose, maltodextrin), 13 to 15 g whey protein, 1 to 2 g leucine, 1 to 2 g glutamine, 60 to 120 mg vitamin C, and 80 to 400 IU vitamin E.

3. The growth phase extends from the end of the anabolic phase to the beginning of the next workout. It represents the time period to maximize insulin sensitivity and maintain an anabolic state to accentuate gains in muscle mass and muscle strength. The first several hours (rapid segment) of this phase helps maintain increased insulin sensitivity and glucose uptake to maximize glycogen replenishment. It also aims to speed elimination of metabolic wastes via increases in blood flow and stimulation of tissue repair and muscle growth. The next 16 to 18 hours (sustained segment) maintains a positive nitrogen balance. This occurs with a relatively high daily protein intake (between 0.91 and 1.2 g of protein per pound of body weight) that fosters sustained but slower muscle tissue synthesis. An adequate carbohydrate intake emphasizes glycogen replenishment.

The recommended *growth phase* supplement profile contains the following nutrients: 14 g whey protein, 2 g casein, 3 g leucine, 1 g glutamine, and 2 to 4 g high-glycemic carbohydrates.

Ivy J, Portman R. Nutrient timing: the future of sports nutrition. North Bergen. NY: Basic Health Publications Inc., 2004.

Summary

- **1.** A kilocalorie (kCal) represents a measure of heat that expresses the energy value of food.
- **2.** Burning food in the bomb calorimeter directly quantifies the food's energy content.
- **3.** The heat of combustion represents the amount of heat liberated by the complete oxidation of a food in the bomb calorimeter. Average gross energy values equal 4.2 kCal per gram for carbohydrate, 9.4 kCal per gram for lipid, and 5.65 kCal per gram for protein.
- **4.** The coefficient of digestibility indicates the proportion of food consumed that the body digests and absorbs.
- **5.** Coefficients of digestibility average 97% for carbohydrates, 95% for lipids, and 92% for proteins. Thus, the net

energy values (known as Atwater general factors) are 4 kCal per gram of carbohydrate, 9 kCal per gram of lipid, and 4 kCal per gram of protein.

- **6.** The Atwater calorific values allow one to compute the caloric content of any meal from the food's carbohydrate, lipid, and protein content.
- 7. The calorie represents a unit of heat energy regardless of food source. From an energy standpoint, 500 kCal of chocolate ice cream topped with whipped cream and hazelnuts is no more fattening than 500 kCal of watermelon, 500 kCal of cheese and pepperoni pizza, or 500 kCal of a bagel with salmon, onions, and sour cream.

Measurement of Human Energy Expenditure

ENERGY RELEASED BY THE BODY

Direct calorimetry and **indirect calorimetry** and the **doubly labeled water technique** represent the most common approaches to accurately quantifying the energy generated by the body (energy expenditure) during rest and physical activity.

Direct Calorimetry

Heat represents the ultimate fate of all of the body's metabolic processes. The early experiments of French chemist Antoine Lavoisier (1743–1794) and his contemporaries (www.science world.wolfram.com/biography/Lavoisier.html) in the 1770s provided the impetus to directly measure energy expenditure during rest and physical activity. The idea, similar to that used in the bomb calorimeter depicted in Figure 6.1, provides a convenient though elaborate way to directly measure heat production in humans.

The human calorimeter illustrated in FIGURE 6.2 consists of an airtight chamber with an oxygen supply where a person lives and works for an extended period.¹ A known water volume at a specified temperature circulates through a series of coils at the top of the chamber. This water absorbs the heat produced and radiated by the individual while in the calorimeter. Insulation protects the entire chamber, so any change in water temperature relates directly to the individual's energy metabolism. For adequate ventilation, the person's exhaled air continually passes from the room through chemicals that remove moisture and absorb carbon dioxide. Oxygen added to the air recirculates through the chamber. Direct



FIGURE 6.2 A human calorimeter directly measures energy metabolism (heat production). In the Atwater-Rosa calorimeter, a thin copper sheet lines the interior wall to which heat exchangers attach overhead and through which water passes. Water cooled to 2°C moves at a high flow rate, rapidly absorbing the heat radiated from the subject during exercise. As the subject rests, warmer water flows at a slower flow rate. In the original bicycle ergometer shown in the schematic, the rear wheel contacts the shaft of a generator that powers a light bulb. In a later version of the ergometer, copper made up part of the rear wheel. The wheel rotated through the field of an electromagnet, producing an electric current for accurately determining power output.

measurement of heat production in humans has considerable theoretical implications, yet its application is limited. Accurate measurements of heat production in the calorimeter require considerable time, expense, and formidable engineering expertise. Thus, use of the calorimeter remains inapplicable for energy determinations for most sport, occupational, and recreational activities.

Indirect Calorimetry

All energy-releasing reactions in the body ultimately depend on oxygen use. Measuring a person's oxygen uptake during aerobic exercise provides an indirect yet accurate estimate of energy expenditure. Indirect calorimetry remains relatively simple to operate and less expensive to maintain and staff than direct calorimetry.

Caloric Transformation for Oxygen

Studies with the bomb calorimeter show that approximately 4.82 kCals release when a blend of carbohydrate, lipid, and protein burns in 1 L of oxygen. Even with large variations in the metabolic mixture, this calorific value for oxygen varies only slightly (generally within 2–4%). Assuming the metabolism of a mixed diet, a rounded value of 5.0 kCal per liter of oxygen consumed designates the appropriate conversion factor for estimating energy expenditure under steady-rate conditions of aerobic metabolism. An energy-oxygen equivalent

of 5.0 kCal per liter provides a convenient yardstick for transposing any aerobic physical activity to a caloric (energy) frame of reference. In fact, indirect calorimetry through oxygen-uptake measurement serves as the basis to quantify the energy (caloric) stress of most physical activities (refer to Appendix B).

Closed-circuit spirometry and open-circuit spirometry represent the two common methods of indirect calorimetry.

Closed-Circuit Spirometry

FIGURE 6.3 illustrates the technique of closed-circuit spirometry developed in the late 1800s and still used in hospitals and some laboratories dedicated to human nutrition research to estimate resting energy expenditure. The subject breathes 100% oxygen from a prefilled container (spirometer). The equipment consists of a "closed system" because the person rebreathes only the gas in the spirometer. A canister of soda lime (potassium hydroxide) in the breathing circuit absorbs the carbon dioxide in exhaled air. A drum attached to the spirometer revolves at a known speed and records oxygen uptake from changes in the system's volume.

Oxygen uptake measurement using closed-circuit spirometry becomes problematic during exercise. The subject must remain close to the bulky equipment, the circuit's resistance to the large breathing volumes in exercise is considerable, and the speed of carbon dioxide removal becomes inadequate during heavy exercise. For these reasons, open-circuit spirom-



FIGURE 6.3 The closed-circuit method uses a spirometer prefilled with 100% oxygen. As the subject breathes from the spirometer, soda lime removes the expired air's carbon dioxide content.

etry remains the most widely used procedure to measure exercise oxygen uptake.

Open-Circuit Spirometry

With open-circuit spirometry, a subject inhales ambient air with a constant composition of 20.93% oxygen, 0.03% carbon dioxide, and 79.04% nitrogen. The nitrogen fraction also includes a small quantity of inert gases. The changes in oxygen and carbon dioxide percentages in expired air compared with those in inspired ambient air indirectly reflect the ongoing process of energy metabolism. Thus, analysis of two factors—volume of air breathed during a specified time period and composition of exhaled air—provides a useful way to measure oxygen uptake and infer energy expenditure.

Four common indirect calorimetry procedures measure oxygen uptake during various physical activities:

- 1. Portable spirometry
- 2. Bag technique
- 3. Computerized instrumentation
- 4. Doubly labeled water technique

PORTABLE SPIROMETRY. German scientists in the early 1940s perfected a lightweight, portable system (first devised by German respiratory physiologist Nathan Zuntz [1847–1920] at the turn of the 20th century) to determine indirectly the energy expended during physical activity.¹¹ Activities included war-related operations such as traveling over different terrain with full battle gear, operating transportation vehicles including tanks and aircraft, and physical tasks that soldiers encounter during combat operations. The subject carried like a backpack the 3-kg box-shaped apparatus shown in FIGURE 6.4. Ambient inspired air passed through a two-way valve, and the expired air exited through a gas meter. The meter measured total expired air volume and collected a small gas sample for later analysis of oxygen and carbon dioxide content. Subsequent determination was made of oxygen uptake and energy expenditure for the measurement period.

Carrying the portable spirometer allows considerable freedom of movement for estimating energy expenditure in diverse activities such as mountain climbing, downhill skiing, sailing, golf, and common household activities (Appendix B). The equipment becomes cumbersome during vigorous activity. Also, the meter under-records airflow volume during intense exercise when breathing is rapid.¹³

Calories Add Up with Regular Exercise

or distance runners who train up to 100 miles weekly, or slightly less than the distance of four marathons at close to competitive speeds, the weekly caloric expenditure from training averages about 10,000 kCal. For the serious marathon runner who trains year-round, the total energy expended in training for 4 years before an Olympic competition exceeds two million kCal—the caloric equivalent of 555 pounds of body fat. This more than likely contributes to the low levels of body fat (3–5% of body mass for men, 12–17% for women) of these highly conditioned yet efficient "metabolic machines."



FIGURE 6.4 ■ Portable spirometer to measure oxygen uptake by the open-circuit method during (A) golf and (B) calisthenics exercise.

Bag Technique. FIGURE 6.5 depicts the bag technique. A subject rides a stationary bicycle ergometer, wearing headgear containing a two-way, high-velocity, low-resistance breathing valve. He breathes ambient air through one side of the valve and expels it out the other side. The air then passes into either large canvas or plastic Douglas bags (named for distinguished British respiratory physiologist Claude G. Douglas [1882–1963]) or rubber meteorologic balloons or directly through a gas meter that continually measures expired air volume. The meter collects a small sample of expired air for analysis of oxygen and carbon dioxide composition. Assessment of oxygen uptake (as with all indirect calorimetric techniques) uses an appropriate calorific transformation for oxygen to compute energy expenditure.⁷

COMPUTERIZED INSTRUMENTATION. With advances in computer and microprocessor technology, the exercise scientist can rapidly measure metabolic and physiologic responses to exercise, although questions have recently been raised concerning accuracy of a widely used computerized breath-by-breath system.⁶

A computer interfaces with at least three instruments: a system that continuously samples the subject's expired air, a flow-measuring device that records air volume breathed and



FIGURE 6.5 Measurement of oxygen uptake during open-circuit spirometry (bag technique) during stationary cycle ergometer exercise.

oxygen and carbon dioxide analyzers that measure the composition of the expired gas mixture. The computer performs metabolic calculations based on electronic signals it receives from the instruments. A printed or graphic display of the data appears throughout the measurement period. More advanced systems include automated blood pressure, heart rate, and temperature monitors and preset instructions to regulate speed, duration, and workload of a treadmill, bicycle ergometer, stepper, rower, swim flume, or other exercise apparatus. FIGURE 6.6 depicts a modular computerized systems approach for collecting, analyzing, and displaying metabolic and physiologic responses during exercise.

Newer portable systems include wireless telemetric transmission of data for metabolic measurement—pulmonary ventilation and oxygen and carbon dioxide analysis—during a broad range of exercise, sport, and occupational activities.³ The lightweight and miniaturized components include a voice-sensitive chip that provides feedback on pacing, duration of exercise, energy expenditure, heart rate, and pulmonary ventilation. The unit's microprocessor stores several hours of exercise data for later downloading to a computer. Telemetry provides "real-time" data on a host computer.

DOUBLY LABELED WATER TECHNIQUE. The doubly labeled water technique provides a useful way to estimate total daily energy expenditure of children and adults in free-living conditions without the normal constraints imposed by other indirect procedures.^{5,18,21} The technique does not furnish sufficient refinement for accurate estimates of an individual's energy expenditure, but is more applicable for group estimates.¹⁶ Because of the expense involved in using doubly labeled water, relatively few subjects participate in research studies. Its accuracy allows doubly labeled water to serve as a criterion for validating other methods (e.g., physical activity questionnaires and physical activity records) for

estimating total daily energy expenditure of groups over prolonged time periods.^{2,4,13}

The subject consumes a quantity of water containing a known concentration of the stable isotopes of hydrogen (²H or deuterium) and oxygen (¹⁸O or oxygen-18)—hence the term *doubly labeled water*. The isotopes distribute throughout all body fluids. Labeled hydrogen leaves the body as water (²H₂O) in sweat, urine, and pulmonary water vapor, while labeled oxygen leaves as water (H₂¹⁸O) and carbon dioxide (C¹⁸O₂) produced during macronutrient oxidation in energy metabolism. An isotope ratio mass spectrometer determines the differences between the two isotopes' elimination relative to the body's normal "background" levels. This procedure estimates total carbon dioxide production during the measurement period. Oxygen consumption (uptake) is easily estimated based on carbon dioxide production and an assumed (or measured) RQ value of 0.85 (see page 181).

Under normal circumstances, a control baseline value for ¹⁸O and ²H is determined by analyzing the subject's urine or saliva before ingesting the doubly labeled water. The ingested isotopes require about 5 hours to distribute throughout the body water. The initial enriched urine or saliva sample is then measured and measured every day (or week) thereafter for the study's duration (usually up to 2 or 3 weeks). The progressive decrease in the sample concentrations of the two isotopes permits computation of carbon dioxide production rate.¹⁷ Accuracy of the doubly labeled water technique versus energy expenditure with oxygen consumption in controlled settings averages between 3 and 5%. This magnitude of error probably increases in field studies, particularly among physically active individuals.²⁰

The doubly labeled water technique provides an ideal way to assess total energy expenditure of groups over prolonged time periods, including bed rest and during extreme activities such as climbing Mt. Everest, cycling the Tour de France, rowing, and endurance running and swimming.^{9,14,19} Major drawbacks of the method include the cost of enriched ¹⁸O and the expense of spectrometric analysis of the two isotopes.

Direct Versus Indirect Calorimetry

Energy metabolism studied simultaneously with direct and indirect calorimetry provides convincing evidence for validity of the indirect method to estimate human energy expenditure. At the turn of the century, Atwater and Rosa compared direct and indirect calorimetric methods for 40 days with three men who lived in calorimeters similar to the one in FIGURE 6.2. Their daily caloric outputs averaged 2723 kCal when measured directly by heat production and 2717 kCal when computed indirectly using closed-circuit measures of oxygen consumption. Other experiments with animals and humans based on moderate exercise also have demonstrated close agreement between the two methods; the difference averaged mostly less than $\pm 1\%$. In the Atwater and Rosa experiments, the $\pm 0.2\%$ method error represents a remarkable achievement given that these experiments relied on handmade instruments.



FIGURE 6.6 Computer systems approach to the collection, analysis, and output of physiologic and metabolic data.

THE RESPIROTORY QUOTIENT

Research in the early part of the 19th century discovered a way to evaluate the metabolic mixture in exercise from measures of gas exchange in the lungs.¹² Because of inherent chemical differences in the composition of carbohydrates, lipids, and proteins, complete oxidation of a molecule's carbon and hydrogen atoms to the carbon dioxide and water end products requires different amounts of oxygen. Thus, the substrate metabolized determines the quantity of carbon dioxide produced relative to oxygen consumed. The **respiratory quotient (RQ)** refers to this ratio of metabolic gas exchange as follows:

$RQ = CO_2$ produced $\div O_2$ consumed

The RQ provides a convenient guide to approximate the nutrient mixture catabolized for energy during rest and aerobic exercise. Also, because the caloric equivalent for oxygen differs somewhat, depending on the macronutrients oxidized, precisely determining the body's heat production or energy expenditure requires knowledge of both the RQ and the oxygen uptake.

RQ for Carbohydrate

The complete oxidation of one glucose molecule requires six oxygen molecules and produces six molecules of carbon dioxide and water as follows:

$$C_6H_{12}O_6 + 6 O_2 \rightarrow 6 CO_2 + 6 H_2O_2$$

Gas exchange during glucose oxidation produces a number of carbon dioxide molecules equal to the oxygen molecules consumed; therefore, the RQ for carbohydrate equals 1.00.

$$RQ = 6 CO_2 \div 6O_2 = 1.00$$

RQ for Lipid

The chemical composition of lipids differs from that of carbohydrates in that lipids contain considerably fewer oxygen atoms in proportion to carbon and hydrogen atoms. (Note the 2:1 ratio of hydrogen to oxygen in carbohydrate matches the ratio in water, whereas fatty acids have a much larger ratio.) Consequently, catabolizing fat for energy requires considerably more oxygen consumed relative to carbon dioxide produced. Palmitic acid, a typical fatty acid, oxidizes to carbon dioxide and water, producing 16 carbon dioxide molecules for every 23 oxygen molecules consumed. The following equation summarizes this exchange to compute RQ:

$$C_{16}H_{32}O_2 + 23 O_2 \rightarrow 16 CO_2 + 16 H_2O$$

 $RQ = 16 CO_2 \div 23 O_2 = 0.696$

Generally, a value of 0.70 represents the RQ for lipid, with variation ranging between 0.69 and 0.73. The value depends on the oxidized fatty acid's carbon chain length.

RQ for Protein

Proteins do not simply oxidize to carbon dioxide and water during energy metabolism. Rather, the liver first deaminates the amino acid molecule. The body excretes the nitrogen and sulfur fragments in the urine, sweat, and feces. The remaining "keto acid" fragment then oxidizes to carbon dioxide and water to provide energy for biologic work. These short-chain keto acids, as with fat catabolism, require more oxygen consumed in relation to carbon dioxide produced to achieve complete combustion. The protein albumin oxidizes as follows:

$$C_{72}H_{112}N_2O_{22}S + 77 O_2 \rightarrow 63 CO_2 + 38 H_2O$$

+ SO₃ + 9 CO(NH₂)₂
RQ = 63 CO₂ ÷ 77 O₂ = 0.818

The general value 0.82 characterizes the RQ for protein.

Estimating Energy Expenditure by Use of the Weir Method

In 1949, J. B. Weir, a Scottish physician/physiologist from Glasgow University, Scotland, presented a simple method, now widely used in clinical research, to estimate caloric expenditure from measures of pulmonary ventilation and the expired oxygen percentage, accurate to within \pm 1% of the traditional RQ method.

Basic Equation

Weir showed that the following formula calculates caloric expenditure (kCal \cdot min⁻¹) if energy production from protein breakdown averaged about 12.5% of total energy expenditure (a reasonable percentage for most persons under typical conditions):

 $kCal \cdot min^{-1} = \dot{V}_{E(STPD)} \times (1.044 - [0.0499 \times \% O_{2E}])$

TABLE 6.3 Weir Factors for Different Expired Oxygen Percentages (%O2E)									
%O _{2E}	Weir Factor	%O _{2E}	Weir Factor	%O _{2E}	Weir Factor	%O _{2E}	Weir Factor		
14.50	.3205	15.80	.2556	17.10	.1907	18.30	.1308		
14.60	.3155	15.90	.2506	17.20	.1807	18.40	.1268		
14.70	.3105	16.00	.2456	17.30	.1857	18.50	.1208		
14.80	.3055	16.10	.2406	17.40	.1757	18.60	.1168		
14.90	.3005	16.20	.2366	17.50	.1658	18.70	.1109		
15.00	.2955	16.30	.2306	17.60	.1707	18.80	.1068		
15.10	.2905	16.40	.2256	17.70	.1608	18.90	.1009		
15.20	.2855	16.50	.2206	17.80	.1558	19.00	.0969		
15.30	.2805	16.60	.2157	17.90	.1508	19.10	.0909		
15.40	.2755	16.70	.2107	18.00	.1468	19.20	.0868		
15.50	.2705	16.80	.2057	18.10	.1308	19.30	.0809		
15.60	.2556	16.90	.2007	18.20	.1368	19.40	.0769		
15.70	.2606	17.00	.1957						

From Weir JB. J Physiol 1949;109:1. If %₀₂ expired does not appear in the table, compute individual Weir factors as 1.044 – 0.0499 × %02_E.

where $\dot{V}_{E(STPD)}$ represents expired ventilation per minute (corrected to STPD conditions), and O_{2E} represents expired oxygen percentage. The value in parenthesis (1.044 - [0.0499 $\times O_{2E}$]) represents the "Weir factor." TABLE 6.3 displays Weir factors for different O_{2E} values.

To use the table, find the \%O_{2E} and corresponding Weir factor. Compute energy expenditure in kCal \cdot min⁻¹ by multiplying the Weir factor by $\dot{V}_{E(\text{STPD})}$.

Example

During a steady-rate jog on a treadmill, $\dot{V}_{E(STPD)} = 50 \text{ L} \cdot \text{min}^{-1}$ and $O_{2E} = 16.0\%$. Energy expenditure by the Weir method computes as follows:

 $\begin{aligned} \text{kCal·min}^{-1} &= \dot{V}_{\text{E(STPD)}} \times (1.044 - [0.0499 \times \%\text{O}_{2E}]) \\ &= 50 \times (1.044 - [0.0499 \times 16.0] \\ &= 50 \times 0.2456 \\ &= 12.3 \end{aligned}$

RQ for a Mixed Diet

During activities ranging from complete bed rest to moderate aerobic exercise (walking or slow jogging), the RQ seldom reflects the oxidation of pure carbohydrate or pure fat. Instead, metabolism of a mixture of these two nutrients occurs, with an RQ intermediate between 0.70 and 1.00. For most purposes, we assume an RQ of 0.82 from the metabolism of a mixture of 40% carbohydrate and 60% fat, applying the caloric equivalent of 4.825 kCal per liter of oxygen for the energy transformation. Using 4.825, a value of 4% represents the maximum error possible when estimating energy metabolism from steady-rate oxygen uptake.

TABLE 6.4 presents the energy expenditure per liter of oxygen uptake for different nonprotein RQ values, including their corresponding percentages and grams of carbohydrate and fat used for energy. The nonprotein value assumes that the metabolic mixture comprises *only* carbohydrate and fat. Interpret the table as follows:

Suppose oxygen uptake during 30 minutes of aerobic exercise averages $3.22 \text{ L} \text{ min}^{-1}$ with carbon dioxide production of 2.78 L min⁻¹. The RQ, computed as VCO₂ ÷ VO₂ (2.78 ÷ 3.22), equals 0.86. From Table 6.4, this RQ value (left column) corresponds to an energy equivalent of 4.875 kCal per liter of oxygen uptake or an exercise energy output of 13.55 kCal · min⁻¹ (2.78 L O₂ · min⁻¹ × 4.875 kCal). Based on a nonprotein RQ, 54.1% of the calories come from the combustion of carbohydrate and 45.9% from fat. The total calories expended during the 30-minute exercise equals 406 kCal (13.55 kCal · min⁻¹ × 30).

Oxygen Uptake and Body Size

To adjust for the effects of variations in body size on oxygen consumption (i.e., bigger people usually consume more oxygen), researchers frequently express oxygen consumption in terms of body mass (termed relative oxygen consumption), as milliliters of oxygen per kilogram of body mass per minute ($mL \cdot kg^{-1} \cdot min^{-1}$). At rest, this averages about 3.5 mL $\cdot kg^{-1} \cdot min^{-1}$, (1 MET) or 245 mL $\cdot min^{-1}$ (absolute oxygen consumption) for a 70kg person. Other means of relating oxygen consumption to aspects of body size and body composition includes milliliters of oxygen per kilogram of fat-free body mass per minute ($mL \cdot kg FFM^{-1} \cdot min^{-1}$) and sometimes as milliliters of oxygen per square centimeter of muscle cross-sectional area per minute ($mL \cdot cm MCSA^{-2} \cdot min^{-1}$).

THE RESPIRATORY EXCHANGE RATIO

Application of the RQ assumes that oxygen and carbon dioxide exchange measured at the lungs reflects the actual gas exchange from macronutrient metabolism in the cell. This assumption remains reasonably valid for rest and during steady-rate (mild to moderate) aerobic exercise when no lactate accumulation takes place. However, factors can spuriously alter the exchange of oxygen and carbon dioxide in the lungs so the ratio of gas exchange no longer reflects only the substrate mixture in cellular energy metabolism. Respiratory physiologists term the ratio of carbon dioxide produced to oxygen consumed under such conditions the **respiratory exchange ratio** (**R** or **RER**). This ratio computes in exactly the same manner as RQ.

For example, carbon dioxide elimination increases during hyperventilation because the breathing response increases to disproportionately high levels compared with actual metabolic demand. By overbreathing, normal carbon dioxide level in blood decreases as this gas "blows off" in expired air. A corresponding increase in oxygen uptake does not occur with this additional carbon dioxide elimination; thus, the rise in respiratory exchange ratio cannot be attributed to the oxidation of foodstuff. In such cases, R usually increases above 1.00.

Exhaustive exercise presents another situation that causes R to rise above 1.00. In such cases, sodium bicarbonate in the blood buffers or "neutralizes" the lactate generated during anaerobic metabolism to maintain proper acid–base balance in the following reaction:

$\label{eq:HLa} \begin{array}{l} \mathsf{HLa} + \mathsf{Na}\mathsf{HCO}_3 \rightarrow \mathsf{Na}\mathsf{La} \, + \, \mathsf{H}_2\mathsf{CO}_3 \rightarrow \mathsf{H}_2\mathsf{O} \\ & + \, \mathsf{CO}_2 \rightarrow \mathsf{Lungs} \end{array}$

Buffering of lactate produces carbonic acid, a weaker acid. In the pulmonary capillaries, carbonic acid degrades to carbon dioxide and water components, and carbon dioxide readily exits through the lungs. The R increases above 1.00 because buffering adds "extra" carbon dioxide to the expired air, in excess of the quantity normally released during energy metabolism.

Relatively low values for R occur following exhaustive exercise when carbon dioxide remains in cells and body fluids to replenish the bicarbonate that buffered the accumulating lactate. This action reduces the expired carbon dioxide without affecting oxygen uptake. This causes the R to dip below 0.70.

TABLE 6.4 Thermal Equivalents of Oxygen for the Nonprotein Respiratory Quotient (RQ), Including Percentage Kilocalories and Grams Derived from Carbohydrate and Lipid								
		Percentage kCal de	rived from	Grams per L O ₂				
RQ	kCal per L O2	Carbohydrate	Lipid	Carbohydrate	Lipid			
0.707	4.686	0.0	100.0	0.000	0.496			
0.71	4.690	1.1	98.9	0.012	0.491			
0.72	4.702	4.8	95.2	0.051	0.476			
0.73	4.714	8.4	91.6	0.090	0.460			
0.74	4.727	12.0	88.0	0.130	0.444			
0.75	4.739	15.6	84.4	0.170	0.428			
0.76	4.750	19.2	80.8	0.211	0.412			
0.77	4.764	22.8	77.2	0.250	0.396			
0.78	4.776	26.3	73.7	0.290	0.380			
0.79	4.788	29.9	70.1	0.330	0.363			
0.80	4.801	33.4	66.6	0.371	0.347			
0.81	4.813	36.9	63.1	0.413	0.330			
0.82	4.825	40.3	59.7	0.454	0.313			
0.83	4.838	43.8	56.2	0.496	0.297			
0.84	4.850	47.2	52.8	0.537	0.280			
0.85	4.862	50.7	49.3	0.579	0.263			
0.86	4.875	54.1	45.9	0.621	0.247			
0.87	4.887	57.5	42.5	0.663	0.230			
0.88	4.889	60.8	39.2	0.705	0.213			
0.89	4.911	64.2	35.8	0.749	0.195			
0.90	4.924	67.5	32.5	0.791	0.178			
0.91	4.936	70.8	29.2	0.834	0.160			
0.92	4.948	74.1	25.9	0.877	0.143			
0.93	4.961	77.4	22.6	0.921	0.125			
0.94	4.973	80.7	19.3	0.964	0.108			
0.95	4.985	84.0	16.0	1.008	0.090			
0.96	4.998	87.2	12.8	1.052	0.072			
0.97	5.010	90.4	9.6	1.097	0.054			
0.98	5.022	93.6	6.4	1.142	0.036			
0.99	5.035	96.8	3.2	1.186	0.018			
1.00	5.047	100.0	0.0	1.231	0.000			

MEASUREMENT OF HUMAN ENERGY GENERATING CAPACITIES

We all possess the capability for anaerobic and aerobic energy metabolism, although the capacity for each form of energy transfer varies considerably among individuals. FIGURE 6.7 shows the involvement of the anaerobic and aerobic energy transfer systems for different durations of all-out exercise. At the initiation of either high- or low-speed movements, the intramuscular phosphagens ATP and PCr provide immediate and nonaerobic energy for muscle action. After the first few seconds of movement, the glycolytic energy system (initial phase of carbohydrate breakdown) provides an increasingly greater proportion of total energy. Continuation of exercise



FIGURE 6.7 Three energy systems and their percentage contribution to total energy output during all-out exercise of different durations.

places a progressively greater demand on aerobic metabolic pathways for ATP resynthesis.

Some physical activities require the capacity of more than one energy transfer system, whereas other activities rely predominantly on a single system. All activities activate each energy system to some degree depending on exercise intensity and duration. Of course, greater demand for anaerobic energy transfer occurs for higher intensity and shorter duration activities.

Both direct and indirect calorimetric techniques estimate the power and capacity of the different energy systems during activity. TABLE 6.5 lists some of the direct and indirect physiologic performance tests in common use for such purposes.

ENERGY EXPENDITURE DURING REST AND PHYSICAL ACTIVITY

Three factors determine total daily energy expenditure (FIG. 6.8):

- 1. Resting metabolic rate, which includes basal and sleeping conditions plus the added energy cost of arousal
- 2. Thermogenic influence of food consumed
- 3. Energy expended during physical activity and recovery

Basal Metabolic Rate

For each individual, a minimum energy requirement sustains the body's functions in the waking state. Measuring oxygen consumption under the following three standardized conditions quantifies this requirement called the **basal metabolic rate (BMR):**

1. No food consumed for at least 12 hours before measurement. The **postabsorptive state** describes this condition

- 2. No undue muscular exertion for at least 12 hours before measurement
- 3. Measured after the person has been lying quietly for 30 to 60 minutes in a dimly lit, temperature-controlled (thermoneutral) room

Regular Exercise Slows a Decrease in Metabolism with Age

ncreases in body fat and decreases in fat-free body mass (FFM) largely explain the 2% decline in BMR per decade through adulthood. Regular physical activity blunts the age-related decrease in BMR. An accompanying 8% increase in resting metabolism occurred when 50- to 65-year old men increased FFM with intense resistance training. Also, an 8-week aerobic conditioning program for older adults, increased resting metabolism by 10% without any change in FFM—indicating that endurance and resistance exercise training can offset the decrease in resting metabolism usually observed with aging.

Maintaining controlled conditions provides a standardized way to study the relationship among energy expenditure and body size, gender, and age. The BMR also establishes an important energy baseline for implementing a prudent program of weight control by food restraint, exercise, or combination of both. In most instances, basal values measured in the laboratory remain only marginally lower than values for the resting metabolic rate measured under less stringent conditions, for example, 3 to 4 hours after a light meal without physical activity. The terms basal and resting metabolism often are applied interchangeably.

TABLE 6.5 Common Direct (Physiologic) and Indirect (Performance) Tests of Human Energy Generating Capacities.								
Energy System	Direct (physiologic) Measures	Indirect (performance test) Measures						
Immediate (anaerobic) system	Changes in ATP/PCr levels for all-out exercise, ≤30 s	Stair-sprinting; power jumping; power lifting						
Short-term (anaerobic) system	Lactate response/glycogen depletion to all-out exercise, ≤3 min	Sprinting; all-out cycle ergometry (e.g., Wingate Test), running and swimming tests						
Long-term (aerobic) system	VO _{2max} ^a assessment; 4 to 20 min duration of maximal incremental exercise	Walk/jog/run/step/cycle tests; submaximal and maximal tests; heart rate response to exercise						

^aHighest oxygen uptake achieved per minute during maximal endurance exercise

Influence of Body Size on Resting Metabolism

FIGURE 6.9 shows that BMR (expressed as kCal per square meter of body surface area per hour; kCal \cdot m⁻² \cdot hr⁻¹) averages 5 to 10% lower in females compared with males at all ages. A female's larger percentage body fat and smaller muscle mass relative to body size helps explain her lower metabolic rate per unit surface area. From ages 20 to 40, average values for BMR equal 38 kCal \cdot m⁻² \cdot hr⁻¹ for men and 36 kCal \cdot m⁻² \cdot h⁻¹ for women.

FACTORS AFFECTING ENERGY EXPENDITURE

Three important factors affect **total daily energy expenditure** (**TDEE**): (1) physical activity, (2) dietary-induced thermogenesis, and (3) climate. Pregnancy also affects TDEE, mainly through its effect of increasing the energy cost of many modes of physical activity.

Components of Daily Energy Expenditure







FIGURE 6.9 Basal metabolic rate (BMR) as a function of age and gender. (Data from Altman PL, Dittmer D. Metabolism. Bethesda, MD: Federation of American Societies for Experimental Biology, 1968.) Inset graph shows the strong relationship between fat-free body mass and daily resting metabolic rate for men and women. (From Ravussin E, et al. Determination of 24-h energy expenditure in man: methods and results using a respiratory chamber. *J Clin Invest* 1968;78:1568.)

Physical Activity

Physical activity profoundly affects human energy expenditure. World-class athletes nearly double their daily caloric outputs with 3 or 4 hours of intense training. Most people can sustain metabolic rates that average 10 times the resting value during "big muscle" exercises such as fast walking and hiking, running, cycling, and swimming. *Physical activity generally accounts for between 15 and 30% TDEE.*

Dietary-Induced Thermogenesis

Consuming food increases energy metabolism from the energy-requiring processes of digesting, absorbing, and assimilating nutrients. **Dietary-induced thermogenesis** (**DIT**; also termed **thermic effect of food**) typically reaches maximum within 1 hour after eating depending on food quantity and type. The magnitude of DIT ranges between 10 and 35% of the ingested food energy. A meal of pure protein, for example, elicits a thermic effect often equaling 25% of the meal's total energy content.

Take a Walk After Eating

ndividuals with poor control over body weight often have a depressed thermic response to eating, an effect most likely related to a genetic predisposition. This can contribute to considerable body fat accumulation over a period of years. Exercising after eating augments an individual's normal thermic response to food intake. This supports the wisdom of "going for a brisk walk" following a meal.

Climate

Environmental factors influence resting metabolic rate. The resting metabolism of people who live in tropical climates, for example, averages 5 to 20% higher than counterparts in more temperate regions. Exercise performed in hot weather also imposes a small additional metabolic load; it causes about a 5% elevation in oxygen uptake compared with the same work performed in a thermoneutral environment. The increase in metabolism comes from a direct thermogenic effect of elevated core temperature plus additional energy required for sweat gland activity and altered metabolism.

Pregnancy

Maternal cardiovascular dynamics follow normal response patterns during pregnancy. Moderate exercise generally presents no greater physiologic stress to the mother other than imposed by the additional weight gain and possible encumbrance of fetal tissue. Pregnancy does not compromise the absolute value for aerobic capacity ($L \cdot min^{-1}$). As pregnancy progresses, increases in maternal body weight add considerably to exercise effort during weight-bearing walking, jogging, and stair climbing and may also reduce the economy of physical effort.

ENERGY EXPENDITURE DURING PHYSICAL ACTIVITY

An understanding of resting energy metabolism provides an important frame of reference to appreciate the potential of humans to increase daily energy output. According to numerous surveys, physical inactivity (e.g., watching television or playing computer games, lounging around the home, and other sedentary activities) accounts for about one third of a person's waking hours. This means that regular physical activity has the potential to considerably boost the TDEE of large numbers of men and women. Actualizing this potential depends on the intensity, duration, and type of physical activity performed.

Researchers have measured the energy expended during diverse activities such as brushing teeth, house cleaning, mowing the lawn, walking the dog, driving a car, playing pingpong, bowling, dancing, swimming, rock climbing, and physical activity during space flight within the space vehicle and outside during work tasks (extravehicular activity [EVA]). Consider an activity such as rowing continuously at 30 strokes per minute for 30 minutes. If the amount of oxygen consumed averaged 2.0 L \cdot min⁻¹ during each minute of rowing, then in 30 minutes the rower would consume 60 L of oxygen. A reasonably accurate estimate of the energy expended in rowing can be made because 1 L of oxygen generates about 5 kCal of energy. In this example, the rower expends 300 kCal (60 L \times 5 kCal) during the exercise. This value represents gross energy expenditure for the exercise period. The net energy expenditure attributable solely to rowing equals gross energy expenditure (300 kCal) minus the energy requirement for rest for an equivalent time.

One can estimate TDEE by determining the time spent in daily activities (using a diary) and determining the activity's corresponding energy requirement. Listings of energy expenditure for a wide range of physical activities are available in Appendix B or can be found on the Internet at various sites (e.g., www.caloriesperhour.com/index_burn.html).

Energy Cost of Recreational and Sport Activities

TABLE 6.6 illustrates the energy cost among diverse recreational and sport activities. Notice, for example, that volleyball requires about 3.6 kCal per minute (216 kCal per hour) for a person who weighs 71 kg (157 lb). The same person expends more than twice this energy, or 546 kCal per hour, swimming the front crawl. Viewed somewhat differently, 25 minutes spent swimming expends about the same number of calories as playing 1 hour of recreational volleyball. Energy expenditure increases proportionately if the pace of the swim increases or volleyball becomes more intense.

Effect of Body Mass

Body weight plays an important contributing role in exercise energy requirements. This occurs because the energy expended during weight-bearing exercise increases directly with the body weight transported. Such a strong relationship exists that one can predict energy expenditure during walking or running from body weight with almost as much accuracy as measuring oxygen consumption under controlled laboratory conditions. In non-weight-bearing or weight-supported exercise (e.g., stationary cycling), little relationship exists between body weight and exercise energy cost.

From a practical standpoint, walking and other weightbearing exercises require a substantial calorie burn for heavier people. Notice in Table 6.6 that playing tennis or volleyball requires considerably greater energy expenditure for a person weighing 83 kg than for someone 20 kg lighter. Expressing caloric cost of weight-bearing exercise in relation to body mass as kCal per kilogram of body weight as kCal per kilogram of body weight per minute (kcal \cdot kg⁻¹ \cdot min⁻¹) greatly reduces the difference in energy expenditure among individuals of different body weights. The absolute energy cost of the exercise (kcal \cdot min⁻¹), however, remains greater for the heavier person.

AVERAGE DAILY RATES OF ENERGY EXPENDITURE

A committee of the United States Food and Nutrition Board (www.lom.edu/cms/3708.aspx) proposed various norms to represent average rates of energy expenditure for men and women in the United States. These values apply to people with occupations considered between sedentary and active and who participate in some recreational activities (i.e., weekend swimming, golf, and tennis). TABLE 6.7 shows that between 2900 and 3000 kCal for males and 2200 kCal for females between the ages of 15 and 50 years represent the average daily energy expenditures. As shown in the lower part of the table, the typi-

TABLE 6.6 Gross Energy Cost (kCal) for Selected Recreational and Sports Activities in Relation to Body Mass												
kg Ib	50 110	53 117	56 123	59 130	62 137	65 143	68 150	71 157	74 163	77 170	80 176	83 183
ACTIVITY Volleyball	12.5	2.7	2.8	3.0	3.1	3.3	3.4	3.6	3.7	3.9	4.0	4.2
Aerobic dancing	6.7	7.1	7.5	7.9	8.3	8.7	9.2	9.6	10.0	10.4	10.8	11.2
Cycling, leisure	5.0	5.3	5.6	5.9	6.2	6.5	6.8	7.1	7.4	7.7	8.0	8.3
Tennis	5.5	5.8	6.1	6.4	6.8	7.1	7.4	7.7	8.1	8.4	8.7	9.0
Swimming, slow crawl	6.4	6.8	7.2	7.6	7.9	8.3	8.7	9.1	9.5	9.9	10.2	10.6
Touch football	6.6	7.0	7.4	7.8	8.2	8.6	9.0	9.4	9.8	10.2	10.6	11.0
Running, 8-min mile	10.8	11.3	11.9	12.5	13.11	3.6	14.2	14.8	15.4	16.0	16.5	17.1
Skiing, uphill racing	13.7	14.5	15.3	16.2	17.0	17.8	18.6	19.5	20.3	21.1	21.9	22.7

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Note: Energy expenditure computes as the number of minutes of participation multiplied by the kCal value in the appropriate body weight column. For example, the kCal cost of 1 hour of tennis for a person weighing 150 lb (68 kg) equals 444 kCal (7.4 kCal \times 60 min).

cal person spends about 75% of the day in sedentary activities. This predominance of physical *inactivity* has prompted some sociologists to refer to the modern-day American as *homo sedentarius*. Compelling evidence supports this descriptor because at least 60% of American adults do not obtain enough physical activity to provide health benefits. In fact, more than 25% of adults receive no additional physical activity at all in their leisure time. Physical activity decreases with age, and sufficient activity becomes less common among women than men, particularly among those with lower incomes and less formal education. Unfortunately, nearly half of youths aged 12 to 21 are not vigorously active on a regular basis.

THE METABOLIC EQUIVALENT (MET)

Values for oxygen consumption and kCal commonly express differences in exercise intensity. As an alternative, a convenient way to express exercise intensity classifies physical effort as multiples of resting energy expenditure with a unit-free measure. To this end, scientists have developed the concept of **METs**, an acronym derived from the term **M**etabolic **E**quivalen**T**. One **MET** represents an adult's average seated, resting oxygen consumption or energy expenditure – about 250 mL $O_2 \cdot \text{min}^{-1}$, 3.5 mL $O_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, 1 kCal $\cdot \text{kg}^{-1} \cdot \text{h}^{-1}$ or 0.017 kCal $\cdot \text{kg}^{-1}$ $\cdot \text{min}^{-1}$ (1 kCal $\cdot \text{kg}^{-1} \cdot \text{h}^{-1} < \text{ds} > 60 \text{ min} \cdot \text{h}^{-1} = 0.017$). Using this frame of reference, a two-**MET** activity requires twice the resting metabolism, or about 500 mL of oxygen per minute; a 3-**MET** intensity level requires three times as much energy as expended at rest, and so on.

The MET provides a convenient way to rate exercise intensity with respect to a resting baseline, that is, multiples of resting energy expenditure. Conversion from MET to kcal \cdot min⁻¹ necessitates knowledge of body mass and use of the conversion: 1.0 kCal \cdot kg⁻¹ \cdot h⁻¹ = 1 MET. For example, if a person weighing 70 kg bicycled at 10 mph, listed as a 10-MET activity, the corresponding kCal expenditure calculates as follows:

10.0 METs = 10.0 kCal \cdot kg⁻¹ \cdot h⁻¹ \times 70 kg <ds> 60 min = 700 kCal <ds> 60 min

= 11.7 kCal \cdot min⁻¹

TABLE 6.7 presents a five-level classification scheme of physical activity based on energy expenditure and corresponding MET levels for untrained men and women.

TABLE 6.7	Average Rates	s of Energy	Expenditur	e for Men and V	Vomen Livi	ng in the United States ^a
	AGE (y)	BODY MASS (kg)	(lb)	STATURE (cm)	(in)	ENERGY EXPENDITURE (kCal)
Males	15–18 19–24 25–50 51+	66 72 79 77	145 160 174 170	176 177 176 173	69 70 70 68	3000 2900 2900 2300
Females	15–18 19–24 25–50 50+	55 58 63 65	120 128 138 143	163 164 163 160	64 65 64 63	2200 2200 2200 1900
		AVER	AGE TIME SP	ENT DURING THE	DAY	
ACTIVITY				TIME	(h)	
Sleeping an	id lying down			8		
Sitting				6		
Standing				6		
Walking				2		
Recreationa	al activity			2		
Data from Food and Nutrition Board, National Research Council: Recommended Dietary Allowances, revised. Washington, DC:						

National Academy of Sciences.

^aThe information in this table was designed for the maintenance of practically all healthy people in the United States.

Summary

- Direct calorimetry and indirect calorimetry are two methods for determining the body's rate of energy expenditure. Direct calorimetry measures actual heat production in an appropriately insulated calorimeter. Indirect calorimetry infers energy expenditure from measurements of oxygen uptake and carbon dioxide production, using closed-circuit spirometry, open-circuit spirometry, or the doubly labeled water technique.
- 2. The doubly labeled water technique estimates energy expenditure in free-living conditions without the normal constraints of laboratory procedures. Although serving as a gold standard for other long-term energy expenditure estimates, drawbacks include the cost of enriched ¹⁸O and the expense of spectrometric analysis of the two isotopes.
- **3.** The complete oxidation of each macronutrient requires a different quantity of oxygen uptake compared to carbon dioxide production. The ratio of carbon dioxide produced to oxygen consumed, termed the *respiratory quotient*, or *RQ*, provides key information about the nutrient mixture

catabolized for energy. The RQ equals 1.00 for carbohydrate, 0.70 for fat, and 0.82 for protein.

- **4.** For each RQ value, a corresponding caloric value exists for each liter of oxygen consumed. This RQ–kCal relationship provides an accurate estimate of exercise expenditure during steady-rate exercise.
- **5.** The RQ does not indicate specific substrate use during non–steady rate exercise because of nonmetabolic carbon dioxide production in the buffering of lactate.
- **6.** The respiratory exchange ratio (R) reflects pulmonary exchange of carbon dioxide and oxygen under various physiologic and metabolic conditions; R does not fully mirror the macronutrient mixture catabolized.
- **7.** Basal metabolic rate (BMR) reflects the minimum energy required for vital functions in the waking state. BMR relates inversely to age and gender, averaging 5 to 10% lower in women than men.

Summary

continued

- **8.** Total daily energy expenditure (TDEE) represents the sum of energy required in basal and resting metabolism, thermogenic influences (particulary the thermic effect of food), and energy generated in physical activity.
- **9.** Body mass, stature, and age, or estimates of fat-free body mass (FFM), provide for accurate estimates of resting daily energy expenditure.
- **10.** Physical activity, dietary-induced thermogenesis, and environmental factors (and to a lesser extent pregnancy) significantly affect TDEE.
- Energy expenditure can be expressed in gross or net terms. Gross (total) values include the resting energy requirement, whereas net energy expenditure reflects the energy

cost of the activity that excludes resting metabolism over an equivalent time interval.

- **12.** Daily rates of energy expenditure classify different occupations and sports professions. Within any classification, variability exists from energy expended in recreational and on-the-job pursuits. Heavier individuals expend more energy in most physical activities than lighter counterparts simply from the energy cost of transporting the additional body mass.
- 13. Different classification systems rate the strenuousness of physical activities. These include rating based on energy cost expressed in kCal · min⁻¹, oxygen requirement in L · min⁻¹, or multiples of the resting metabolic rate (METs).

Test Your Knowledge Answers

- True: In nutritional terms, one calorie expresses the quantity of heat needed to raise the temperature of 1 kg (1 L) of water 1°C (specifically, from 14.5 to 15.5°C). Thus, kilogram-calorie or kilocalorie (kCal) more accurately defines a calorie.
- 2. False: Laboratories use the bomb calorimeter to measure the total energy value of the various food macronutrients. Bomb calorimeters operate on the principle of direct calorimetry, measuring the heat liberated as the food burns completely.
- 3. False: Heat of combustion refers to the heat liberated by oxidizing a specific food; it represents the food's total energy value as measured by the bomb calorimeter. The oxidation pathways of food in the intact organism and bomb calorimeter differ, yet the energy liberated in the complete breakdown of food remains the same regardless of the combustion pathways.
- 4. False: The heat of combustion for carbohydrate varies depending on the arrangement of atoms in the particular carbohydrate molecule. On average, for 1 g of carbohydrate, a value of 4.2 kCal generally represents the average heat of combustion.
- 5. False: The heat of combustion for lipid varies with the structural composition of the triacylglycerol molecule's fatty acid components. The average heat of combustion for lipid equals 9.4 kCal per gram.
- False: The coefficient of digestibility represents the percentage of an ingested macronutrient actually digested and absorbed by the body. The quantity of

food remaining unabsorbed in the intestinal tract becomes voided in the feces. The relative percentage digestibility coefficients average 97% for carbohydrate, 95% for lipid, and 92% for protein.

- 7. False: The doubly labeled water technique estimates total daily energy expenditure of children and adults in free-living conditions without the normal constraints imposed by other procedures of indirect calorimetry. It involves the ingestion of stable isotopes of hydrogen and oxygen, which distribute throughout all body fluids. Differences between elimination rates of the two isotopes relative to the body's normal "background" level estimates total carbon dioxide production from energy metabolism during the measurement period.
- 8. False: The average net energy values can be rounded to simple whole numbers and are referred to as Atwater general factors, which are as follows: 4 kCal per gram for carbohydrate, 9 kCal per gram for lipid, 4 kCal per gram for protein.
- 9. True: The more one eats of any food, the more calories one consumes. An individual's caloric intake equals the sum of all energy consumed from either small or large quantities of foods. Thus, celery becomes a "fattening" food if consumed in excess. Achieving this excess involves consuming a considerable quantity of celery. For example, the typical sedentary woman needs to consume 420 celery stalks, yet only 8 oz of salad oil, to meet her daily 2100 kCal energy needs.

continued

Test Your Knowledge Answers

10. True: Inherent chemical differences in the composition of carbohydrates, lipids, and proteins means that the complete oxidation of a molecule's carbon and hydrogen atoms to carbon dioxide and water end products requires different amounts of oxygen. Gas exchange during glucose oxidation produces six carbon dioxide molecules for six oxygen molecules consumed. Therefore, the RQ (CO₂ produced \div O₂ consumed) for carbohydrate equals 1.00. (RQ = 6 CO₂ \div 6 O₂ = 1.00).

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