Public Health Nutrition: 8(7A), 1123–1132 DOI: 10.1079/PHN2005800

Measurement of energy expenditure

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Abstract
Measurement of energy expenditure in humans is required to assess metabolic needs, fuel utilisation, and the relative thermic effect of different food, drink, drug and emotional components. Indirect and direct calorimetric and non-calorimetric methods for measuring energy expenditure are reviewed, and their relative value for measurement in the laboratory and field settings is assessed. Where high accuracy is required and sufficient resources are available, an open-circuit indirect calorimeter can be used. Open-circuit indirect calorimeters can employ a mask, hood, canopy or room/chamber for collection of expired air. For short-term measurements, mask, hood or canopy systems suffice. Chamber-based systems are more accurate for the long-term measurement of specified activity patterns but behaviour constraints mean they do not reflect real life. Where resources are limited and/or optimum precision can be sacrificed, flexible total collection systems and non-calorimetric methods are potentially useful if the limitations of these methods are appreciated. The use of the stable isotope technique, doubly labelled water, enables total daily energy expenditure to be measured accurately in free-living subjects. The factorial method for combining activity logs and data on the energy costs of activities can also provide detailed information on free-living subjects.

Keywords
Total energy expenditure
Calorimetry
Doubly labelled water
Thermogenesis
Basal metabolic rate
Accelerometers
Hear rate monitors

Introduction

There are three components to total energy expenditure (TEE) in humans: basal metabolic rate (BMR), thermic effect of food and the energy expenditure of activity (activity thermogenesis). BMR is the energy expended when an individual is lying at complete rest, in the morning after sleep in the post-absorptive state. In individuals with sedentary occupations basal metabolic rate accounts for approximately 60% of the total daily energy expenditure and is highly predicted by lean body mass within and across species. Resting energy expenditure, in general, is within 10% of the BMR and is measured in subjects at complete rest in the post-absorptive state. Thermic effect of food is the increase in energy expenditure associated with digestion, absorption and storage of food, and accounts for approximately 10% of the total daily energy expenditure; many believe there exist facultative as well as fixed components. Activity thermogenesis is the thermogenesis that accompanies physical activities and, therefore, can be divided into exercise and non-exercise activity thermogenesis (NEAT). Most individuals do not partake in purposeful sporting exercise and so their exercise-related activity thermogenesis is zero; for those who do exercise regularly, exercise-related energy expenditure is generally ~10% of the total daily energy expenditure. NEAT or the 'energy expenditure of spontaneous physical activity' encompasses the combined energy costs of the physical activities of daily living, fidgeting, spontaneous muscle contraction and maintaining posture when not recumbent, and accounts for the remainder of the total daily energy expenditure for most individuals. Other thermogenic variables may also need to be considered, such as the energetic costs of altered temperature, medications and emotion.

Each of these components of energy expenditure is highly variable and the total effect of these variances determines the variability in daily energy expenditure between individuals. Also, measurements of energy expenditure can be used to assess the *relative* thermic effects of different foods, nutrient compositions, beverages, medications and psychological components.

Description of methods

Energy expenditure can be measured using one of the three approaches:

1. In *indirect calorimetry*, oxygen consumption and/or carbon dioxide production is measured and converted to energy expenditure using formulae[1,2].
2. In *direct calorimetry*, the rate of heat loss from the subject to the calorimeter is measured.
3. A number of *non-calorimetric* techniques have been used to predict the energy expenditure by extrapolation from physiological measurements and observations.

The accuracy, reproducibility and reliability of the measurements obtained using these various techniques

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vary enormously as the complexity and cost of the techniques themselves. The techniques are summarised in Table 1.

Indirect calorimetry

There are five principal approaches to the measurement of energy expenditure using indirect calorimetry.

Total collection systems

Here, expired air is collected in either an airtight rigid structure or a portable flexible bag.

Rigid total collection system

The Tissot Gasometer is an example of a rigid total collection system[3]. It comprises a 100–1000 litre capacity inverted glass bell fitted with an internal circulation fan suspended over water. The bell is emptied of air. The subject then expires through a mouthpiece and a non-return valve into the bell, which gradually fills with expired air and progressively rises above the water seal. The height reached by the bell is recorded every minute for up to 2 hours and the composition of expired air is periodically measured from the bell to determine oxygen consumption and/or carbon dioxide production.

Flexible total collection system

The Douglas bag[4–7] is an example of a flexible total collection system. It comprises a polyvinyl chloride (or other leak-proof material) bag of typically 100–150 litre capacity. The top of the bag is connected by tubing to a three-way valve which may be rotated to either seal the bag, admit atmospheric air or admit expired air via tubing attached to a respiratory valve. To use this approach, the three-way valve is first rotated to open the circuit to atmospheric air, the bag is rolled up to expel its contents and the three-way valve then rotated to seal the bag. The subject breathes through the mouthpiece and the three-way valve is rotated to allow the expired air for 10–20 minutes. After the timed collection period, the three-way valve is turned to seal the bag. An alternative valve system employs two valves, one at the mouthpiece and the other proximal to the bag. Several bags can be used to prolong the total measurement period[8]. After collection of the expired air, the volume of the expired air in the bag is measured (for example using a mass flow meter) and a sample is analysed to determine oxygen and/or carbon dioxide concentrations. Under optimal conditions the error of energy expenditure measurements undertaken with Douglas bags may be very small (<3%) but can increase substantially if the equipment is poorly maintained, the volume, oxygen and/or carbon dioxide measurements inaccurate and/or the operator untrained or unskilled.

Open-circuit indirect calorimeter systems

Open-circuit systems can be used to record energy expenditure over several hours or days depending upon the configuration selected and the experimental requirements. In an open-circuit system, the subject inspires air and the expired gases are then analysed. There are two types of open-circuit systems: ventilated open-circuit systems where a subject breathes into a container through which air is drawn, and expiratory collection systems where a subject inspires from the atmosphere and expires via a non-return valve into a measurement unit.

Ventilated open-circuit systems

In general, ventilated open-circuit systems comprise components to collect and mix expired air, measure flow rate, analyse gas concentrations and pump air through the system.

The method of collecting expired air varies considerably. The least complex approach is for expired air to be collected using a mouthpiece, mask, transparent hood or canopy[9–13]. Measurements can be performed for up to several hours. The most more complex approach is for the subject to be placed inside a room/chamber of known volume in which there are often sophisticated sensing

Table 1 Summary of techniques used to measure energy expenditure in humans

Approach	Type of calorimeter	Basal metabolic rate	Resting energy expenditure	Thermic effect of food	Energy expenditure of specific activities	Total daily energy expenditure
Indirect calorimeter	Room open-circuit	Yes	Yes	Yes	Yes	Yes (confined subject)
	Hood/canopy open-circuit	Yes	Yes	Yes	Yes	No
	Open-circuit expiratory collection	Yes*	Yes*	Yes*	Yes	Yes*
	Doubly labelled water	No	No	No	No	Yes
	Total collection Douglas bag	Yes	Yes	Yes*	Yes	No
Direct calorimeter		Yes	Yes	Yes	Yes	Yes (confined subject)
Non-calorimetric methods		No	No	No	No	Estimated

'Yes' represents where a technique can be used to perform the respective measurement and 'No' where it cannot.
*Precision may be unreliable.

https://doi.org/10.1079/PHN2005800 Published online by Cambridge University Press

devices to quantify physical activity[14]. Using a room or chamber, measurements can be performed for up to several days[15–17].

Regardless of how the expired air is collected, the basic components of ventilated open-circuit indirect calorimeters are similar. Expired air is drawn out of the collection device using a pump; it is critical to measure this flow rate accurately. The expired air is then mixed using a fan and/or mixing chamber, and a sample of the expired air is dried and analysed for oxygen and/or carbon dioxide concentrations. Oxygen is generally analysed by using paramagnetic analysers and carbon dioxide by using infrared analysers; alternatively, a mass spectrometer can be used to measure the gas concentrations. Burning known masses of chemical standards, such as butane or ethanol, within the system and ascertaining what proportion of the burned mass is detected by the calorimeter verifies the precision of these calorimeters. Ventilated open-circuit indirect calorimeters have precision to within 0.5–2% of actual.

Depending on the software, air mixing and room volume, response time for a room or chamber system can vary from ~5 to 30 minutes; for a ventilated hood or canopy, ~2 minutes and for a mask or mouthpiece <30 seconds. Hood/canopy/mask-based systems are often configured as a 'metabolic cart' whereby the equipment could be readily moved on a wheeled cart. Finally, it is important that inspired carbon dioxide should not exceed 1%[12] as concentrations in excess of this may increase respiratory effort.

Expiratory collection open-circuit systems

There are several expiratory collection open-circuit systems. The advantage of this approach is that the calorimeter can be designed as a portable device so that energy expenditure can be measured in free-living individuals. In general, these devices comprise a mouthpiece or a mask connected to a one-way valve whereby expired air enters the instrument. The flow rate of expired air through the valve is measured and a small proportion of the expired air is diverted to a gas storage reservoir that is analysed at the end of each measurement period. Measurements can be carried out using such instruments intermittently for up to 2 days. Various modifications have been applied to this principle; for example, by having air drawn through the system at a fixed rate[18,19]. Technological advance[20,21] has resulted in the design of more precise, robust and dependable portable calorimeters that are likely to provide useful field data in the future.

Confinement system (respiratory chambers)

The subject is placed inside a gas-tight sealed container of known volume (e.g. 16 m^3)[22] and oxygen consumption and carbon dioxide production are estimated from changes in the concentrations of these gases in chamber air over time[23]. The period of observation may be prolonged by periodically flushing the chamber with fresh air. A number of confinement systems have been constructed with errors of ~2% and response times of ~50 minutes. Currently, confinement systems are rarely used.

Closed-circuit systems

Closed-circuit systems consist of a sealed respiratory gas circuit in which gaseous concentrations are measured over time[24]. In one conformation, expired air was drawn from a sealed 5 m^3 chamber. Carbon dioxide and water vapour were absorbed and then oxygen was reintroduced into the air stream, which re-entered the chamber. Energy expenditure was calculated from the quantities of carbon dioxide absorbed and oxygen re-introduced. A small-scale application of this approach was to use a spirometer. A spirometer consists of an oxygen-containing bell from which the subject inspires; expired carbon dioxide and water vapour are absorbed before the expired air is reintroduced to the bell. The bell is suspended over water so that its height descends at a rate proportional to oxygen consumption. Closed-circuit systems are rarely used at present.

Direct calorimetry

An exhaustive description of the different types of direct calorimeter is beyond the scope of this paper. In general, the instruments are extremely expensive to build (>$1 000 000) and run, requiring at least one full-time technician. They require enormous expertise to establish and maintain and offer little to the majority of investigators beyond less expensive and complex indirect calorimeters. Application of direct calorimetry is in the domain of highly specialised laboratories where direct heat loss measurements are of specific value.

Direct calorimeters measure the heat lost from the body. Radiative and convective heat losses account for approximately 80% of the total heat loss, while evaporative heat loss accounts for the remainder. Conductive heat loss is negligible in humans.

There are three principal types of direct calorimeter: isothermal, heat sink and convection systems. These approaches have on occasion been used in combination.

Isothermal systems

An isothermal calorimeter consists of a chamber lined with a layer of insulating material[25]. The inner aspect of the layer is in thermal equilibrium with the inside of the chamber and the outside aspect of the layer is in thermal equilibrium with the chamber wall, which is maintained at a constant temperature using circulating fluid. The temperature gradient across the insulating layer is proportional to the non-evaporative heat loss from the subject in the calorimeter. The response time of these

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instruments can be <5 min and measurement error (under optimal operator application) is 1%.

Heat sink or adiabatic systems

These calorimeters consist of a chamber from which heat lost by the subject is extracted by a liquid-cooled heat exchanger[26]. The rate of heat extraction is regulated so that the temperatures of the inner and outer chamber walls are equal, producing a 'zero temperature gradient wall'. The response time of these instruments is 10–30 minutes and measurement error is 1–2%. A 'suit calorimeter' was devised based on this principle. The suit weighed <10 kg and could be worn by a subject for up to 48 hours[27]. Although evaporative heat loss was impaired by this device, measurement error was <3%.

Convection systems

These calorimeters consist of an insulated chamber ventilated with an air flow at a known rate. Heat lost by a subject inside the chamber is calculated from the flow rate, the specific heat capacity of the air and the increase in temperature of ventilating air leaving the chamber[28–30]. The response time of these instruments is 10–20 minutes and measurement error is 1–2%.

Non-calorimetric methods for measuring TEE

Non-calorimetric methods estimate energy expenditure by extrapolation from variables that relate to energy expenditure. These methods are often standardised against calorimetric methods.

Isotope dilution, doubly labelled water

In the doubly labelled water method, both the hydrogen and the oxygen of water are labelled or 'tagged' using stable, non-radioactive isotopes (D_2O^{18})[31–36]. Elimination of administered D_2O^{18} may be used to estimate carbon dioxide production and energy expenditure.

The principle of this technique is as follows. In body water, O_2 of expired CO_2 is in equilibrium with O_2:

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$

Thus, if O_2 in body water is tagged with the tracer O^{18}, the label will distribute in not only body water but also circulating H_2CO_3 and expired CO_2. Over time, the concentration of O_2 label in body water will decrease as CO_2 is expired and body water is lost in urine, perspiration and respiration. If H_2 in body water is tagged with the tracer D_2, the label will distribute solely in the circulating H_2O and H_2CO_3. Over time, the concentration of H_2 label will decrease as body water is lost (some of the hydrogen can become portioned into body protein or fat, however). Thus, if both O_2 and H_2 in body water are tagged with known amounts of tracers at the same time, the differences in the elimination rates of the O_2 and H_2 tracers will represent the elimination rate of CO_2.

Subjects are usually given doubly labelled water orally after baseline samples of urine, saliva or blood have been collected. Time is allowed for complete mixing of isotopes to occur within the body water space and then samples of urine, saliva or blood are collected over 7–21 days. These samples are used for the measurements of D_2 and O^{18} enrichments using mass spectroscopy. Changes in D_2 and O^{18} concentrations in body water are then calculated over time, and CO_2 production and energy expenditure are calculated. Energy expenditure can be measured over 7–21 days using this technique with an error of ~6–8%. This error can be decreased to a small degree by collecting samples repeatedly over the measurement period rather than by collecting them only before and after the measurement period.

Physiological measurements

Heart rate monitoring

In humans, there is a significant relationship between heart rate and energy expenditure, at least in the absence of exercise. Heart rate monitors are portable, non-restraining and unobtrusive and measurements can be carried out over several days. A number of devices of varying complexity have been used to record heart rate in free-living subjects[37–45]. The conceptual limitation of this approach is that energy expenditure and heart rate are not linearly related for an individual in part because cardiac stroke volume changes with changing heart rate and even posture. There is a substantial inter-individual variance for the relationships between heart rate and energy expenditure in terms of slope, intercept and curve characteristics. Furthermore, variance in covariables that affect heart rate, such as emotion, also impact the 'heart rate/energy expenditure' relationship. Hence, precision of heart rate prediction of energy expenditure is improved where a separate regression equation is derived to relate heart rate to energy expenditure for each individual. Some investigators use multiple regression equations for each subject. At best, the mean (±95% confidence limits) error for estimating energy expenditure using heart rate monitoring is 3 ± 20% during light activity.

Integrated electromyography

Muscular activity is a component of energy expenditure and can be measured using integrated electromyography (EMG). Here, cumulative electrical muscle activity from several muscle fibres is measured and the data accumulated over the measurement period. However, strength/force relationships differ for different muscle groups and fibres, and multiple muscle groups need to be measured in order to gain a representative assessment of whole-body activity. These limitations make this technique impractical[46,47].

Pulmonary ventilation volume

Measurement of pulmonary ventilation volume (direct measurement of the volume of gas exchanged over time)

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may provide an estimate of energy expenditure but this technique is impractical for use other than for very short periods of time[48,49].

Thermal imaging
Limited precision and accuracy and the complexity of data processing complicated the early studies that employed thermal imaging to detect human heat loss to the environment. More recent studies have employed automated, high-resolution, rapid-response thermal imaging[50] and offer promise for future studies, particularly in the area of thermoregulation[51].

Physiological observations

Activity recall and time-and-motion studies
Non-specific information about habitual activity and NEAT can be obtained using questionnaires, interviews or time-and-motion studies. Predictably, substantial errors are introduced through inaccurate recall and inadequate data recording. These approaches can be used, however, for following trends in certain activities, particularly in relation to occupational practices[52].

Activity logs and the factorial method
This is a frequently used approach for estimating activity thermogenesis and, in particular, NEAT in free-living individuals. First, a subject's physical activities are logged over the time period of interest (e.g. 1 week). The energy equivalent of each of these activities is measured or estimated using a calorimeter or tables[18,53,54]. The time spent in each activity is then multiplied by the energy equivalent for that activity. These values are then summed to derive an estimate of activity thermogenesis. This determination of activity thermogenesis is often combined with information on basal metabolic rate (measured or calculated) to estimate total daily energy expenditure.

There are two potential sources of error for the factorial approach for measuring activity thermogenesis. First, errors may result from inaccurate recording of activities and, second, from inaccurate determinations of the energy costs of the activities. To log activity, subjects are often asked to record in a diary the nature and amount of time spent performing each of their activities throughout the day[55]. This has several limitations: subjects may be illiterate or innumerate, they may report their activities inaccurately or incompletely and/or may alter their normal activity patterns during the period of assessment. To limit these sources of error, one approach is to have trained enumerators to follow subjects and objectively record the subjects' activities[52]. This approach is time consuming and expensive but potentially a valuable source of accurate and objective data. For this purpose, newer image-gathering technologies may be useful in future for this purpose. To determine the energy costs of physical activities, standard tables are often used. However, these may introduce substantial (albeit systematic) errors. First, the tables may not include the precise activity the subjects perform. Second, the energy cost for a given activity is highly variable between subjects even independent of gender. Third, calorimetric methods for measuring the energy costs of activities have not been standardised between investigators so that precision and accuracy of data in the activity tables cannot always be assured. To limit these errors, the energy costs of each or most of the activities that the subjects of interest perform can be measured using calorimeters, as described above. At best, the energy costs for each subject's activities would be measured, but clearly this is rarely practical except for small studies. In general, population-gender-age specific group means for the majority of the studied subjects' activities represents a standard that is worth achieving where optimum precision is warranted.

Kinematic measurements
In kinematic measurements, a subject's movements are quantified and these measurements are usually performed in conjunction with other measures of energy expenditure. These tools are used primarily to estimate the energy cost of NEAT ('spontaneous physical activity').

Some techniques are specific for confined spaces such as radar tracking and cine photography[56,57]. Other techniques have been used in free-living individuals and generally focus on pedometers and accelerometers of varying sophistication. Pedometers typically detect the displacement of a subject with each stride. However, pedometers tend to lack sensitivity because they do not quantify stride length or total body displacement and overall, therefore, become poor predictors of activity thermogenesis[58]. Accelerometers detect body displacement electronically with varying degrees of sensitivity; uniaxial accelerometers in one axis and triaxial accelerometers in three axes. Portable uniaxial accelerometer units have been widely used to detect physical activity[59–61]. Careful evaluation demonstrates that these instruments are not sufficiently sensitive to quantify the physical activity of a given free-living subject but rather they are more valuable for comparing activity levels between groups of subjects. Greater precision has been obtained using triaxial accelerometers[62–64]. In free-living subjects, data from these devices correlate well with the total daily energy expenditure, measured using doubly labelled water, divided by basal metabolic rate[65]. The utility of motion tracking using approaches such as Global Positioning Systems has not been fully defined for human studies.

Practical recommendations for measurement techniques

The choice of measurement technique is determined by the objective of the assessment, the resources available and the ability and willingness of the subjects to partake.

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Each investigator needs to define which components of the energy expenditure are to be measured, in what setting and with how much resource.

Laboratory setting

To provide precise and accurate short-term (several hours) measurements of energy expenditure in the laboratory, well-validated and frequently calibrated indirect or direct calorimeters should be used. For a relatively modest cost (US$ 10 000–20 000) a hood/canopy/mask indirect open-circuit calorimeter can be purchased. These instruments are fully automated and simple for a technician with moderate skill to use, validate and calibrate. The instruments are often configured as a 'metabolic cart' and therefore are transportable although often not portable. Measurements to within 1% of chemical standards can be obtained using these instruments, which can be used for measurements of basal metabolic rate and resting energy expenditure. Measurements of the energy expenditure of specific activities (e.g. hair brushing or walking) and even VO_2 max measurements can be made if the calorimeter's flow rate is adequate to prevent CO_2 accumulation, and if the accuracy and precision of flow-rate measurements are maintained at higher oxygen consumptions.

Recently, modestly priced (US$ 1000–20 000), open-circuit expiratory collection calorimeters have been produced with adequate precision (<3% error) for basal metabolic rate, resting energy expenditure measurements as well as the determination of the energy costs of specific activities. These instruments may allow widespread measurements of these variables and their true application will become apparent over the next several years.

Where investigators wish to make laboratory-based determinations of *the total daily energy expenditure*, greater financial investment is necessary. A room calorimeter can be built to provide accurate measurements of energy expenditure over a longer term (1–2 days). It should be recognised that this is a major undertaking. Unless the application of the investigators argues against it, constructing an indirect room calorimeter is simpler and less costly than a direct calorimeter. Room or chamber calorimeters require dedicated space, should be equipped with some means of detecting and quantifying physical activity within the room or chamber and will necessitate at least one full-time, highly skilled technician to maintain, validate, calibrate and use the instrument. Even with maximum precision (<1% error), it should be noted that subjects within these chambers are confined and are unable to perform the activities of daily living.

Regardless of which measurement approach is selected, it is necessary to adhere to rigorous validation and calibration protocols. Validation involves burning a measured mass of a standard of known energy equivalent within the calorimeter and ascertaining what proportion of this standard is detected by the calorimeter. Examples of such standards include ultra-pure butane and ethanol. These chemical validations should be performed monthly and have been simplified by the availability of commercially available equipment. Optimum precision for a calorimeter is to within 3% of predicted and optimum precision is to within 1% of predicted; this latter goal is readily achievable with careful attention to technique and detail.

Calibration should be performed before each measurement and at intervals during the measurement period to protect against sensor drift. An indirect calorimeter calibration involves the use of standard gases. It is recommended that two span gases be used that cover the spectrum of oxygen and/or carbon dioxide concentrations that occur during human measurements. With improved sensor linearity, many systems employ a single-span gas with 100% nitrogen as the second calibration gas. It is critical to ensure that the composition of the calibration gases is guaranteed, that the accepted standard for calibration gases is to what is termed 'primary gas standard'. Flow sensor calibration is more challenging and some systems allow verification of flow sensor validity by displacing fixed volumes of gas through the system using a gas syringe of several litre capacity. Another approach is to use detachable flow sensors that can be shipped to the manufacturer for verification of precision. For direct calorimeters, calibration is performed before each measurement using a heat emitter of known energy dissipation. By adopting rigorous standards of validation and calibration, data will be more reliable and so readily disseminated and exchanged between laboratories.

Field setting

Calorimeter techniques

There is a paucity of high-quality data pertaining to activity-related energy expenditure[66]. Modern tools may allow this concern to be re-addressed. Several precise, portable, expiratory collection, open-circuit, indirect calorimeters have been developed recently (as modifications of older devices such as the Kofranyi–Michaelis respirometer[19]) and these may facilitate field-base measurements of energy expenditure at rest and with routine activities. Douglas bags can be used in the field for measuring basal metabolic rate, resting energy expenditure and, in particular, the energy expenditure of physical activities. Douglas bags may not necessarily be an inexpensive option, however. There are the combined costs of purchasing and maintaining high-quality bags and high-precision sensors for volume and gas concentration measurements and, because the technique is highly operator dependent, skilled technicians are needed. Experienced technical support, well-maintained Douglas bags and precise, validated and calibrated instrumentation are needed to obtain high-quality data using this approach. Conceptually, metabolic carts can be used in

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the field but this rarely occurs because of constraints such as terrain and electricity supply.

Non-calorimetric methods

Field-based measurements of total daily energy expenditure over 7–21 days can be obtained using doubly labelled water. Administration of the isotopes is straightforward in that O^{18} and D_2 are weighed, subjects drink the mixture and collect urine, saliva or blood samples before and after administration. As discussed above, some investigators recommend daily sample collection whereas others collect samples before and after the collection period. Specimens are readily transportable, they are not radioactive and stable isotopes do not decay over time. Thus, as long as the samples are well sealed, measurement of enrichments can be performed even in another country at any time after collection. Often, indirect calorimetry is used to measure BMR in conjunction with the total daily energy expenditure measurements obtained using doubly labelled water. Activity thermogenesis can thereby be calculated (the thermic effect of food is generally assumed to equal 10% of the total daily energy expenditure).

The major advantage of doubly labelled water measurements is that accurate measurements (error of ~7%) of total daily energy expenditure are obtained in truly free-living individuals. There are important limitations, however. First, no information is obtained regarding the components of activity thermogenesis. Second, the thermic effect of food is not measured and is known to be variable (most believe this to introduce only a small error). Third, O^{18} is expensive (~$700/subject), thereby potentially limiting the number of subjects that can be studied. Fourth, isotope ratio mass spectrometers are expensive to purchase and maintain and skilled staff are needed for their use; hence, collaboration is encouraged between field investigators and laboratories where these instruments are in routine use. It is expected that this approach to field-based measurement of energy expenditures will become more widespread despite its costs and limitations.

Logging physical activity and multiplying the nature and duration of these activities by their metabolic equivalents have been widely used to estimate activity thermogenesis. Overall, this approach is potentially valuable, particularly as the components of activity thermogenesis are detailed. The precision and accuracy of the approach is highly variable, however, and depends on how precisely the subjects' activities are recorded and how accurately these are transformed to energy expenditures. It is important to note that the errors of this approach are additive. Where maximum precision is needed in small studies, trained enumerators might be used and measurements are made of the energy expenditures of typical activities in representative individuals using calorimeters. Where less precision is acceptable and where study populations are larger, activity diaries combined with meaningful (e.g. gender-specific) tables of energy equivalents for representative activities are likely to provide useful group data, particularly for following population trends.

Techniques have been developed to facilitate more accurate measurements of body motion and other components of physical activity in free-living individuals. There are examples where such measures correlate well with measured TEE obtained using doubly labelled water[65].

Overall, progress is being made to obtain data on energy expenditure in free-living individuals. It is expected that these technological advances can be exploited to provide improved measures of energy expenditure in the field.

Standardisation of protocols

Once equipment is available to perform measurements of energy expenditure, adhering to standardised protocols has several advantages. First, it allows comparisons to be made between different laboratories. Second, it enables databases to be generated to explore the variance in the components of energy expenditure and better characterise the energy expenditure of physical activities and free-living physical activity in different individuals and populations.

Basal metabolic rate

BMR should be measured between 06.00 and 09.00 hours in individuals who slept at the site of measurement overnight. The individuals should not have consumed food or energy-containing beverage for 9 hours prior to the measurement but may have consumed water. The measurement should be performed with the patient supine. A single pillow may support the subject's head and/or the head of the bed should be at a 10° vertical tilt. The subject should be in thermal comfort and the room should not be brightly lit. Subjects should be instructed to lie motionless and should not be allowed to talk or have other potentially stimulating distractions during the measurement. The measurement period should last for 20–40 minutes.

Resting energy expenditure

Resting energy expenditure should be performed in the post prandial state, at least 6 hours after consumption of any calories or performing any rigorous activity. Subjects should be fully rested while supine for 60 minutes prior to the measurement. The measurement is otherwise as described for BMR.

Thermic effect of food

Optimally, a measurement of BMR should be performed first, then subjects should be provided with a meal of food. The energy content of the food should be known precisely and should be of 400 kcal or greater. Energy expenditure should then be measured for 400 minutes or until energy expenditure falls to within 5% of the BMR. For those using

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hood-based systems (with response time <2 minutes), energy expenditure can be measured for every 15 minutes out of 30 minutes to avoid subject agitation. The thermic effect of food for the meals provided is calculated from the area under the energy expenditure above basal metabolic rate versus the time curve. Some would argue that it is of value to also measure the thermic effect of non-caloric meals.

Energy expenditure of physical activities
Points of reference are important. Resting energy expenditure should be measured first, then the energy expenditure of the posture of reference should be measured while the subject is motionless. For example, for measuring the energy expenditure of secretarial work, sitting energy expenditure should be measured as the point of reference. For measuring the energy expenditure of scything, standing energy expenditure should be measured as the point of reference. Measurement of energy expenditure during the performance of the activity of interest should be performed for 10–20 minutes if the calorimeter has a response time of <2 minutes. Where calorimeter response times are longer, the measurement period needs to be prolonged so that steady-state energy expenditure is reached. The energy expenditure for the activity can be calculated as the steady-state energy expenditure for that activity minus (or divided by) either the energy expenditure of the posture of reference or the resting energy expenditure.

Areas for future research

There are a number of areas for future research with respect to energy expenditure measurements.

- *Integration of data on energy expenditure.* With standardisation of technical standards and techniques, it would be advantageous to develop international databases on BMR, resting energy expenditure, energy expenditure of specific activities and total daily energy expenditure measured using doubly labelled water. This would facilitate validation of energy requirement recommendations and allow cross-cultural investigation into metabolic rate variance.
- *Physical activity in free-living individuals.* Technology is fast improving to provide detailed and accurate information on NEAT and the types and quantities of physical activities that individuals perform. It is recommended to readily employ novel and advanced technologies once they have been validated in representative populations.
- *Doubly labelled water collaborative agreements.* It is recommended to establish a collaborative environment for the analysis of doubly labelled water determinations. It is proposed to identify laboratories where isotope enrichments can be analysed so that studies can be performed by other investigators lacking necessary instruments. This would facilitate studies of TEE in under-developed countries.
- *Non-calorimeter methods.* The role of newer technologies such as thermal imaging or global positioning remains to be determined but should be explored.

Acknowledgements

Funded by NIH DK56650, DK63226 and DK66270.

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