# Estimating human energy expenditure: a review of techniques with particular reference to doubly labelled water

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# Estimating Human Energy Expenditure

## A Review of Techniques with Particular Reference to Doubly Labelled Water

*Philip N. Ainslie*,[1] *Thomas Reilly*[2] and *Klass R. Westerterp*[3]

1 Department of Physiology and Biophysics, University of Calgary, Faculty of Medicine, Calgary, Alberta, Canada
2 Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK
3 Department of Human Biology, Maastricht University, Maastricht, The Netherlands

## Contents



## Abstract

This review includes an historical overview of the techniques for measuring energy expenditure (EE). Following this overview, the 'gold standard' method of measuring EE, the doubly labelled water (DLW) method, is emphasised. Other methods, such as direct calorimetry, indirect calorimetry systems, heart rate and EE relationships, questionnaires and activity recall, motion sensors, combined heart rate and motion sensors for the estimation of EE are then highlighted in relation to their validation against the DLW method. The major advantages and disadvantages for each method are then considered. The preferred method to determine EE is likely to depend principally on factors such as the number of study participants to be monitored, the time period of measurements and the finances available. Small study participant numbers over a short period may be measured accurately by means of indirect calorimetric methods (stationary and portable systems). For periods over 3–4 days, EE should ideally be measured using the DLW method. However, the use of motion sensors is very promising in the measurement of EE, and has a number of advantages over the DLW method. Furthermore, if used correctly, both heart rate and questionnaire methods may provide valuable estimates of EE. Additional studies are needed to examine the possibility of improving the accuracy of measurement by combining two or more techniques. Such information, if confirmed by scientific rigour, may lead to an improvement in the estimation of EE and population-based physical activity levels. The accurate measurement of physical activity and EE is critical from both a research and health prospective. A consideration of the relevant techniques used for the estimation of EE may also help improve the quality of these frequently reported measurements.

The development of objective and valid methods for assessing energy expenditure (EE) in population- and work-based studies is an important goal. Such methods would be useful in assessing the strength and nature of the association between physical inactivity and health. Their use would also be relevant to evaluating occupational strain in an ergonomics context. They could be employed in monitoring the changes in EE within populations over time and in describing international and cross-cultural differences. Finally, they would be of considerable utility in the evaluation of interventions aimed at increasing physical activity or monitoring the energy cost of any human activities. In the context of the present review, the difference between EE and physical activity can be explained firstly by referring to basal metabolic rate (BMR). For example, EE is normally expressed in absolute units and is influenced by inter-individual differences in BMR, which is largely dependent on body size. The BMR is the lowest level of energy expended at rest. Physical activity is a behaviour that is characterised by any body movement that results in an increase in EE above resting levels;[1] it is usually expressed in units that are independent of inter-individual differences in BMR which is, in most individuals, a relatively small component of total EE. The net energy cost of activity may vary between individuals due to differences in mechanical efficiency; however, this variation is small for the majority of human activities.

There is a range of methods that are used in the assessment of EE. In this review, only those methods that have gained acceptance among researchers are considered. Each approach has its own advantages and disadvantages. This review differs from its predecessors[2-4] in that the use of doubly labelled water (DLW) is chosen as the reference method. The present purpose is to review some of the main practical methods used in the measurement of EE. Where appropriate, the various methods will be highlighted in relation to their validation against the DLW method. Recommendations are made for the most useful practical measurement tool, after consideration of factors such as the type and duration of activity, expense, and sample size.

## 1. Historical Overview of the Measurement of Energy Expenditure (EE) Techniques

The scientific study of animal respiration was first recorded in the 1600s. In 1660, Robert Boyle observed that mice that had been sealed in bell jars, expired at the same time as a burning flame was extinguished. Thus, Boyle established two important principles, namely the equivalence of fire and life as combustion processes and the requirement of air to support these processes.[5] Of greater significance was the work of John Mayrow in 1668.[6] Mayrow observed that mice died when they had consumed about one-fourteenth of the air in a bell jar. Mayrow accordingly established the idea that air consists of different parts, only some of which are usable for the process of respiration. This idea led to the invention of a chamber that allowed the quantification of the consumed portion; this chamber was the first respirometer.

A century after the innovative work of Boyle and Mayrow, the French chemists Lavoisier and Seguin started systematic studies of respiration as a process analogous to combustion. The procedures used by Lavoisier and Seguin closely mimicked those developed by Mayrow, the key difference being the framework within which the observations were interpreted.[6] Lavoisier and Seguin made several important discoveries about oxygen consumption ($\dot{V}O_2$). Firstly, they found that larger people consume more oxygen than smaller people. Secondly, people sitting quietly at rest were found to consume less oxygen than those standing up or moving around. Finally, they discovered that $\dot{V}O_2$ was elevated after a meal. Perhaps most importantly, Lavoisier and Seguin established the methodology of indirect calorimetry that has remained the benchmark for quantifying animal and human EE to this day.

The chambers within which animals and humans are confined have become increasingly sophisticated since the end of the 18th century. Moreover, sealed systems have been replaced with open-flow systems linked to advanced gas analysis equipment. Nevertheless, such chambers will never be able to reproduce the complexity of activities in which people are engaged as they go about their daily lives. The inadequacy of traditional calorimetry has been recognised for some time, and there have been many attempts to develop methods, such as heart rate (HR) and motion monitoring, that enable energy demands associated with free-living activities to be determined.[6,7] The DLW method allows the energy demands of free-living subjects (both humans and animals) to be measured. The success of this method prompted Prentice[8] to remark that its development was as significant an event in the history of animal and human nutrition, as the work of Lavoiser and Sequin had been earlier. The DLW method subsequently became the 'gold standard' for the measurement of total EE and forms a method against which other approaches may be validated.[6,8,9]

## 2. Methods for the Measurement of EE: Overview and Considerations

### 2.1 Direct versus Indirect Calorimetry

Direct calorimetry measures total heat loss from the body; indirect calorimetry measures total energy production by the body. With the former, the study participant is placed in a thermally-isolated chamber, and the heat they dissipate (by evaporation, radiation, conduction and convection) is recorded accurately and measured precisely.[10] In indirect calorimetry, on the other hand, $CO_2$ production and $\dot{V}O_2$ are what are really measured. Assuming that all the oxygen is used to oxidise degradable fuels and all the $CO_2$ thereby evolved is recovered, it is possible to calculate the total amount of energy produced.[10] In this review, only indirect calorimetry and its extensions will be considered, as direct calorimetry is of limited practical interest in the present context of total energy output by free-living populations.

### 2.2 Doubly Labelled Water (Free-Living Indirect Calorimetry)

The use of DLW for the assessment of free-living EE in humans was first reported by Schoeller and van Santen,[11] and the technique has been evaluated subsequently.[8,9,12] This method provides information on the total energy expended by a free-living individual for a period of 4–20 days, a period likely to reflect the normal energy requirement of the individual. The individual takes an oral dose of water containing a known amount of stable (non-radioactive) isotopes of both hydrogen and oxygen. The isotopes, $^2H$ (deuterium) and $^{18}O$, mix with the normal hydrogen and oxygen in the body water within a few hours. As energy is expended in the body, $CO_2$ and water are produced. The $CO_2$ is lost from the body in breath, whilst the water is lost in breath, urine, sweat and other evaporations. As $^{18}O$ is contained in both $CO_2$ and water, it is lost from the body more rapidly than $^2H$, which is contained in water but not in $CO_2$.

The difference between the rate of loss of $^{18}O$ and $^{2}H$ reflects the rate at which $CO_2$ is produced, which in turn can be used alone to estimate EE. However, an estimate of the ratio of $CO_2$ production to $\dot{V}O_2$ makes the calculation more reliable. This estimate can be done in any of three main ways. Firstly, a value for the respiratory quotient can be assumed, based on a standard Western diet.[13] Secondly, the individual keeps a diary of food intake, and this is used to assess the ratio of $CO_2$ production to $\dot{V}O_2$ if all this food is combusted (the food quotient); it is reasonable to assume that the same ratio for the body (the respiratory quotient or respiratory exchange ratio) will approximate the food quotient over a period of time.[14,15] Finally, the $CO_2$ production relative to $\dot{V}O_2$ can be measured using established methods incorporating indirect calorimetry techniques (see section 2.3). A plot of the change in concentrations of the two isotopes in body fluids, from which the rate of loss of these isotopes from the body fluid can be calculated, is shown in figure 1.

The utility of the DLW method in measuring total EE is demonstrated by its use in a variety of settings. These include the measurement of total EE in all age groups, including premature infants, hospitalised patients, children, obese people, pregnant and lactating women and the elderly, for whom other methods might have serious problems.[13] The applications of DLW include the validation of techniques for the assessment of dietary intake and physical activity, assessment of energy requirement, and the assessment of the effect of dietary and physical activity interventions, including its use with endurance athletes competing at the highest level.[13]

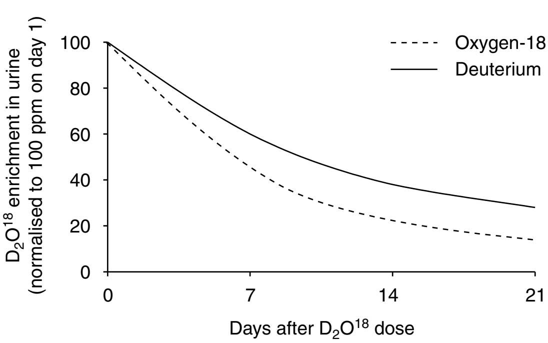


**Fig. 1.** Decline of $^{2}H$ (deuterium [D]) and $^{18}O$ in body fluids (urine, plasma or saliva) during a hypothetical doubly labelled water experiment.

The DLW method is not without some disadvantages, despite its clear advantages. These include: (i) the high cost of the $^{18}O$, and the specialised expertise required for the analysis of the isotope concentrations in body fluids by mass spectrometry; (ii) total EE is measured over about 4–21 days, so no knowledge is obtained about brief periods of peak expenditure; and (iii) in field studies, because $CO_2$ production and not oxygen utilisation is being measured, some error (approximately 5%) is introduced if the respiratory quotient is not known.[13] Nevertheless, the fact that the results provide the closest measure of free-living EE, makes the DLW method an extremely valuable reference technique for validating estimates of energy requirements obtained by other methods. The validation of the DLW method has been described thoroughly by Schoeller and Hnilicka.[16]

### 2.3 Indirect Calorimetry Systems

There are two main indirect calorimetry systems for the measurement of $\dot{V}O_2$ and hence EE. Firstly, the 'closed-circuit' method requires the study participant to be isolated from the outside air. Normally, the respirometer originally contains pure oxygen, and as the study participant breathes in this closed system the $CO_2$ is continuously removed as it passes through soda lime. The gas volume gradually decreases, and the rate of decrease is a measure of the rate of $\dot{V}O_2$. Over shorter durations, oxygen is not required for measurements of $\dot{V}O_2$. The study participant absorbs his/her produced $CO_2$ and $H_2O$ with the corresponding volume change reflecting the $\dot{V}O_2$. This method works reasonably well for measuring resting or basal metabolic rate; however, absorbing the large volume of $CO_2$ produced during prolonged, strenuous exercise becomes a problem.

Secondly, the 'open-circuit' method is more suited to measuring exercise metabolism. Two main procedures in the open-circuit method have been developed. In one, the flow-through technique,[2] a large volume equivalent to the outside air passes through a hood worn by the study participant. The study participant inspires and expires into the airstream flowing through the hood. Airflow and percentage of oxygen and $CO_2$ are measured precisely to calculate $\dot{V}O_2$ and $CO_2$ consumption ($\dot{V}CO_2$) and hence respiratory exchange ratio. This method is particularly useful for long-term measurements with the study participant at rest or performing only light exercise.

The second procedure, the time-honoured Douglas bag method (although a meteorological balloon is commonly used), is accurate and theoretically sound. With this procedure, the study participant wears a nose clip and mouthpiece, or a facemask. Outside air or its equivalent is inhaled through the mouthpiece or mask containing a one-way valve and exhaled into a Douglas bag or Tissot tank. The volume of air in the bag or tank is measured to calculate minute ventilation. A sample of air is obtained to measure the oxygen and $CO_2$ concentrations. The method of measurement and appropriate formula to calculate $\dot{V}O_2$, $\dot{V}CO_2$ and hence EE are important, and have been described by Elia and Livesey.[2]

In the laboratory, modern online electronic equipment usually replaces the Douglas bag method, whereby ventilation, oxygen and $CO_2$ percentages are determined instantaneously and continuously. The electronic equipment confines the procedure to the laboratory. The Douglas bag method is not as restrictive because a bag can be carried on the back or by an assistant close by, permitting its use in the field.

#### 2.3.1 Indirect Calorimetry Systems (Portable)

Zuntz and Leowy[17] recognised the advantage of having the study participant carry a self-contained unit if $\dot{V}O_2$ is to be measured during exercise. They developed what was probably the first such unit, which resembles a large rucksack. This was a forerunner of the portable calorimeter designed by Kofranyi and Michaelis[18] that was subsequently improved by Wolff[19] and later modified by Humphrey and Wolff.[20] The system designed by Humphrey and Wolff,[20] called the Oxylog™**1**, was a battery-operated, self-contained, portable instrument, weighing about 3kg, but was engineered for measurement of $\dot{V}O_2$ online. $CO_2$ was not measured and so an respiratory exchange ratio value was assumed. It has been found to be reasonably accurate in field measurements during rest and up to moderately strenuous exercise.[21,22]

Advances in technology have produced a range of portable systems which can also measure $CO_2$ production and breath-by-breath pulmonary gas exchange. These systems, namely the Metamax™ (Borsdorf, Germany) and, lately, the Cosmed K4 b2™ (Rome, Italy), are the most recent on the market. The K4 b2™ device is the new portable system designed by Cosmed to measure gas exchange on a true breath-by-breath basis during any kind of activity. The system is fully portable while also allowing breath-by-breath pulmonary gas exchange measurements, direct field assessment of human performance and cardiopulmonary limitations during any kind of activity. The K4 b2™ machine has the same facilities as a laboratory station and is light weight (600g), which helps to ensure individual comfort as well as portability. However, measurements using these portable systems are normally limited to 1–5 hours. In addition, the expense of the systems would normally only allow study participants to be monitored on an individual basis. Both the Metamax™ and K4 b2™ systems have been validated and found to provide good accuracy and reliability for measurements of respiratory gas exchange at rest and during exercise.[23,24] However, further testing is needed to assess the accuracy of both systems using a range of exercise modes under various environmental conditions. Although there are some other portable systems available on the market, e.g. the Aerosport™ system, they have limited use in the assessment of EE during 'free-living' conditions. For a comprehensive review of indirect calorimetry systems, readers are directed to an excellent review by Macfarlane.[4]

**1** The use of tradenames is for product identification purposes only and does not imply endorsement.

 

### 2.4 Heart Rate and EE Relationships

During exercise, there is a fairly close relationship between heart rate (HR) and EE, so records of HR allow an estimate of EE to be made. In order to allow for the variation in fitness between individuals, a calibration curve based on simultaneous measurements of HR and $\dot{V}O_2$, using indirect calorimetry in a variety of activities, must be made for each individual.[25] A typical human response curve, illustrated in figure 2, shows how at low levels of EE, HR does not increase as steeply for a given change in EE, probably due to changes in stroke volume between lying, sitting and standing. This may be one reason why 24-hour estimates of EE from HR may have errors of up to 30% in individuals, although the average for a group of individuals is likely to be within 10% of the true value.[25-27]

Monitoring of HR also provides information on the amount of time spent in high-intensity activity, which may be useful for assessment of physical activity rather than EE. Furthermore, it provides a relatively cheap method of estimating EE. However, HR is affected by factors other than physical activity. For example, such factors as emotional stress, high ambient temperature, high humidity, dehydration, posture and illness can all cause changes in HR without associated changes in $\dot{V}O_2$.[3,25,26,28,29] The size of the muscle group engaged may also influence the relationship, HR being elevated for a given $\dot{V}O_2$ during arm exercise compared with exercise with the legs or with both arms and legs.[30]

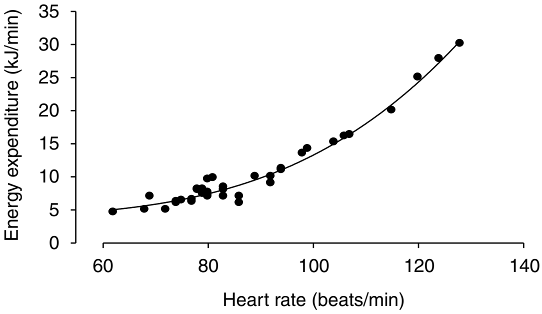


**Fig. 2.** The relationship between heart rate and energy expenditure in a healthy male study participant (unpublished data).

Although there are a number of ways to assess the data from HR monitoring, the optimum method for the estimation of EE is called the FLEX HR method.[29] With this method, each individual is monitored simultaneously for HR and $\dot{V}O_2$ while lying down, sitting, standing, and performing exercise at a variety of intensities. In addition, resting metabolic rate is often obtained from each individual. This information is then used to develop the individual's HR-$\dot{V}O_2$ curve. The FLEX HR is quantified by the average of the highest HR from resting/sedentary activity and the lowest HR from light activity. If a given HR observed during field activity is below the FLEX HR, then resting metabolic rate is used to determine the EE. If a given HR is above FLEX HR, the calibration curve is used to estimate EE. Despite the advantage of this method, it does prove both costly and time consuming. Although a group calibration may be used to avoid the excess time, this strategy has been shown to increase the error of estimating EE.[31] Furthermore, the calibration curve is specific to the activities performed in the laboratory and may not accurately reflect the EE of field activities and hence free-living.[27,31] Another important consideration is that the HR monitors are not well tolerated by individuals for time periods representative of daily life for 1 week or more.

Livingstone et al.[32] investigated the utility of the FLEX HR method for estimating total daily EE by comparing it with the DLW method. The study revealed individual estimates of EE from the FLEX HR that ranged from −16.7% to 18.8% of the DLW determinants. When examined on a group basis, the estimate was +10% of the DLW measurements of EE.[32]

In summary, although HR is a physiological marker for physical activity, it can be influenced by factors other than activity. Whilst it gives an indication of the overall physiological strain, it may not be the best method available for obtaining an estimate of EE. Thus, while it may be sufficient for providing a general picture of activity, it may not be the method of choice for obtaining an estimate of EE.

 

### 2.5 Questionnaires and Activity Recall

There is a range of questionnaires and activity recall methods available for the assessment of EE in humans. Only the questionnaires that have been validated against DLW are described and considered in this review. A literature search has yielded five different methods that have been used in combination against the DLW method. These questionnaires include: (i) activity (or log) and recall questionnaires; (ii) the Baecke questionnaire; (iii) the Five-City questionnaire; (iv) the Tecumseh questionnaire; and (v) the Yale Physical Activity Survey (YPAS).

Studies on activity questionnaires incorporated a 1-week[33] or 2-week activity diary,[34] three 7-day activity recall questionnaires,[35,36] the Physical Activity Scale for the Elderly (PASE),[37] the Baecke questionnaire, the Five-City questionnaire, and the adapted version of the Tecumseh Community Health study questionnaire.[38] The YPAS is a recently developed interviewer-administered questionnaire for the elderly.[39]

The activity diary method has been described by Bouchard et al.[40] Individuals record at every 15 minutes of the waking day a number corresponding to one of a group of categories[33] or 12 activity categories,[37] according to their average physical activity during that time period. Numbers are converted to the average daily metabolic rate by multiplying the integrated mean 24-hour activity score with the measured BMR. The 'activity recall' method includes a standard questionnaire that categorises activities by their intensity, using the compendium of Ainsworth et al.[41,42] EE is then calculated by multiplying the amount of time spent in each activity by the corresponding metabolic equivalent. Reilly and Thomas[43] used diary cards for monitoring habitual activities of professional footballers outside training and competition. The EE in training and competition was estimated using HR and work-rate data, respectively. The daily EE values of 14.442MJ corresponded with more recent estimates based on DLW.[44] The PASE is a brief questionnaire designed by Washburn et al.[45] It comprises activities commonly engaged in by elderly persons, and the reference period is 1 week. The PASE score is the sum of the time spent in each activity, multiplied by an item weight factor. Also designed for use in the elderly, the YPAS assesses a typical week of activity and examines household, exercise and recreational activities. The survey is normally administered during a 20-minute interview by a trained investigator. Physical activity EE is calculated based on total time per week in each specific activity. The test-retest correlation coefficient over 2 weeks has been shown to be 0.42–0.65 in 71-year-old women and men.[39]

Baecke et al.'s inventory is a brief questionnaire with three categories (work, sport and leisure) adding up to give a total activity index.[46] The Five-City questionnaire requires the time spent in very hard-, hard-, moderate- and light-intensity activities and sleeping to be recorded. Each category is multiplied by the reported hours and a weight factor to calculate an activity index. The Tecumseh questionnaire is an adapted version of that designed by Reiff et al.[47] Individuals are interviewed on the estimated hours per week of sports participation, home repair and maintenance activities, sleeping and eating, quiet leisure time and remaining activities. The hours per week are multiplied by the physical activity level values listed by Ainsworth et al.[41,42] to obtain a figure for total activity. Another commonly used interviewer-administered questionnaire that assesses daily physical activity is the Minnesota Leisure Time Physical Activity Questionnaire (MLTPA).[48] The MLTPA assesses daily physical activity accumulated during leisure time and household activities over the past 12 months. Leisure time physical activity is calculated based on the number of days spent completing the specific activity each month, total time per each specific activity session, and an activity-specific code. The test-retest correlation coefficient over the month has been shown to be 0.92 in 20- to 59-year-old women and men.[49] The average daily physical activity EE is then subsequently calculated.

Most of the studies on activity questionnaires have shown an association between the derived activity score and the DLW assessment of EE (table I).

**Table I.** Correlation between the activity score of questionnaires and the doubly labelled water-assessed physical activity level

| Questionnaire | No. of study participants | Correlation coefficient or % difference | Reference |
|---|---|---|---|
| Activity diary | 6 | 0.72** | 34 |
| Activity diary | 50 | 1.2% | 33 |
| Activity recall | 13 | 0.67* | 35 |
| Activity recall | 19 | 0.52* | 36 |
| Activity recall | 13 | 5% | 53 |
| Activity recall | 27 | 9.8–37.4% | 54 |
| PASE | 21 | 0.68** | 37 |
| Activity recall | 24 | 30.6% | 51 |
| Baecke questionnaire | 19 | 0.69*** | 38 |
| Five-City questionnaire | 19 | 0.42 | 38 |
| Tecumseh questionnaire | 19 | 0.64** | 38 |
| Tecumseh questionnaire | 24 | 7.9% | 51 |
| Tecumseh combined with MLTPA | 24 | 8.9% | 50 |
| MLTPA | 77 | 59% | 52 |
| MLTPA | 13 | 0.74* | 55 |

**MLTPA** = Minnesota Leisure Time Physical Activity Questionnaire; **PASE** = Physical Activity Scale for the Elderly; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

As expected, an activity diary was superior to activity recall. Both the Baecke and the Tecumseh questionnaires showed strong correlations when compared with the DLW method. Likewise, the PASE and the MLTPA showed strong correlations in some of the studies[50,51] but not all.[52] The index of the Five-City questionnaire was not significantly related to the DLW method. The questionnaires considered in this review were selected for their comparison against the DLW method for estimating EE. This selection only represents a relatively small sample of the well-established questionnaires that may be of equal benefit in establishing physical activity levels in large population-based studies.

In summary, questionnaire and activity recall methods are of clear advantage when used in large population-based and/or epidemiological studies. The important consideration is to use the appropriate questionnaire/recall method in relation to the specific individual cohort investigated. Finally, despite some strong correlations between the DLW gold-standard method and the various questionnaires (table I), care should be expressed in the interpretation of these data since strong bivariate relationships do not necessarily imply agreements between the two methods.[56-58] Ideally, as used by Starling et al.,[52] future comparative studies should correctly compare their data in terms of 'limits of agreement'.

## 2.6 Motion Sensors

Motion sensors are mechanical and electronic devices that pick up motion or acceleration of a limb or trunk, depending on where the monitor is attached to the body.[59,60] There are several types of motion sensors that range in complexity and cost from the pedometer to the triaxial accelerometer. Accelerometers detect total body displacement electronically with varying degrees of sensitivity: uniaxial accelerometers in one axis and triaxial in three axes. Descriptions of each motion sensor have been described in detail elsewhere.[45,53,61-71] The aim of the next section is to briefly review the main sub-groups of motion sensors and evaluate their merit in estimating EE against the DLW method, where possible.

### *2.6.1 Pedometers*

Pedometers typically detect the displacement of physical objects with each stride.[3] The pedometer counts steps by responding to vertical acceleration, trigger a lever arm to move vertically and a ratchet to rotate.[3] The main advantages of pedometers are that they are generally small and low in cost (table II).[3,60] However, pedometers tend to lack sensitivity as they do not quantify stride length or total body displacement[3,72] and are therefore of very limited utility in predicted EE. Despite this limitation, if overall walking activity is the outcome to be assessed, the pedometer is a useful and inexpensive instrument, particularly in walking intervention studies where participants can self-monitor their behaviour to determine if they are attaining specified goals.[59,60,73]

#### 2.6.2 Uniaxial Accelerometers

Portable uniaxial accelerometer units, such as the Caltrac™ and Computer Science Applications™ (CSA)**2** accelerometers, have been widely used to detect walking.[64] The theoretical basis underlying the use of a accelerometers to assess physical activity is that acceleration is directly proportional to the muscular forces and therefore related to EE.[3,28] These units are small (Caltrac™, 7 × 7 × 2cm; CSA, 5.1 × 3.8 × 1.5cm), unobtrusive instruments with large memory capacity that allow for monitoring and storage of temporal patterns of activity during time intervals of days to weeks. Additionally, the accelerometers measure both the amount and intensity of movement. However, not all activity is reflected in acceleration or deceleration such as load carriage or on a gradient.[3,64] This failure to record activity leads to large errors in predicted EE, especially participants engaged in high-intensity activity.

There has been a number of validations of the Caltrac™ and CSA, in a wide range of populations and age groups, against both indirect calorimetry measurements[28,63,64,66,89-93] and the DLW method.[52,53,55,94,95]

Although both the Caltrac™ and CSA have shown relatively strong correlations when compared with measurements of indirect calorimetry to estimate EE, there seems to be a general overestimation of EE during these periods of activity.[28,63,64,66,89-93] When compared with the DLW method, some studies have demonstrated a significant underestimation of free-living EE of 50–59% in older men,[52] 59% in young females[53] and (mean difference of –658 ± 379 kcal/day; n = 26) in children.[95] Conversely, other comparative studies in obese women[94] and older claudicants[55] have shown a significant overestimation of EE (50–60%) when using the uniaxial accelerometers when compared with the DLW method.

The literature described suggests that both the Caltrac™ and CSA sensors are not sufficiently sensitive to quantify EE in free-living individuals, but rather they are more valuable for comparing activity levels between groups of individuals.[59,63,73,96]

#### 2.6.3 Triaxial Accelerometers

Triaxial accelerometers measure acceleration in the vertical, horizontal, and mediolateral planes. The Tritrac R3D™ (Hemokinetrics, Inc., Madison, WI, USA) and, more recently, the Tracmor™ (Maastricht, The Netherlands) are the most commonly used triaxial accelerometers. Both of these units have provided increased precision in application to walking to the estimation of EE over the uniaxial accelerometer devices. The Tritrac™ and Tracmor™ provide a measure of counts in each plane as well as vector magnitude over a specified time interval. Additionally, total and activity EE is estimated that uses a prediction equation to estimate BMR using age, body mass and sex as independent variables.[45]

The Tracmor™ triaxial accelerometer has been relatively well validated[70,71,83] and the results are promising. This unit has several advantages besides being lightweight and portable.[83] First, the units have been validated against a motor-driven rotating arm where test-to-test repeatability is within ~0.5%.[83] Secondly, conditions for optimum usage have been defined (e.g. site of attachment of acceler-

**2** Although the Caltrac™ and CSA motion sensors have been extensively described in the literature, there are a number of other commercial systems available (e.g. The Actillume Actigraph™ [Ambulatory Monitoring, Inc., Ardsely, NY, USA]; Kenz Accelerometer™, Select 2 Model™ [Nagoya, Japan]; The Biotrainer™ [IM Systems, Baltimore, MD, USA]). Compared with the Caltrac™ and CSA, these systems have received few validation studies and are subsequently not discussed in the present review.

**Table II.** Summary of key techniques

| Technique | Typical no. of individuals per test | Duration of use | Cost ($US; 2002 values)[a] | Advantages | Limitations | Available models/ manufacturer information | References |
|---|---|---|---|---|---|---|---|
| Direct calorimetry | 1 | 1–7d | NA | Direct and precise measure of EE | Non-free living; only one individual can be monitored at one time; large expense of measurements | No manufacturers; normally made by specialist engineers | 10,74-77 |
| DLW | 1 | 1–3wk | 1000–1500 | Applicable to a range of individuals and field conditions, EE is measured over long periods, is safe and does not interfere with normal physiological conditions | High costs of $^{18}O$ – limits large group application; requires sophisticated equipment for analysis, error introduced if FQ is not known, no information can be gained about brief or specific periods of activity | Isotec™ (USA); Marshall Isotopes™ (Israel); Cambridge Isotopes™ (Adover, MA, USA) | 8,9,11-13,16 |
| Indirect calorimetry | 1 | <9h | 20 000–60 000 | Accurate in the measurement of EE and fuel utilisation during rest and steady-state exercise | Cannot assess 'free living' EE; expense of systems | Oxycon Pro™ (Jaegar, Germany); Oxycon Alpha™ (Jaegar, Germany); ParvoMedics™ (Sandy, UT, USA); Pulmolab EX670™ (Morgan Mecial, Kent, UK) | 2,4,78 |
| Indirect calorimetry – portable systems | 1 | <9h | 20 000–60 000 | Individual assessment of EE during a range of activities; reusable | Cost and small group usage; invalid estimation of EE during non-steady-state activities | Oxylog™ (Morgan Mecial, Kent, UK); Metamax™ (Cortex Biophsik GmbH, Germany); K4 b$^{2}$™ (Cosmed, Rome, Italy) | 20-23,79 |

*Continued next page*

**Table II.** Contd

| Technique | Typical no. of individuals per test | Duration of use | Cost ($US; 2002 values)[a] | Advantages | Limitations | Available models/ manufacturer information | References |
|---|---|---|---|---|---|---|---|
| Heart-rate monitoring | 1 | 1–3wk | 200–600 | Provides information on the amount of time spent in high-intensity activity; cheap and reusable | Affected by factors other than physical activity; large potential error in estimating EE | Polar Electro™ (Oy, Kempele, Finland) | 25-27,32 |
| Questionnaires, activity and dietary recall | 1 | Unlimited; 1–2wk | Cost of paper | Low cost; possible to study large individual cohort | Poor individual compliance and recoding errors; EE estimates are based predominantly on males, limited number validated against DLW | | 33,34,36,38 41,42,51,52 54,80-82 |
| Motion sensors | 1 | 1–2wk | 200–400 | Excellent means to evaluate interventions aimed at increasing physical activity; low cost and use in a large population range | Uniaxial sensors: not sufficiently sensitive to quantify EE; triaxial; measurement of acceleration in the vertical, horizontal, and mediolateral planes. Provides a more meaningful measurement of EE but still limited in precision | Yamax™ (New Lifestyles Inc., MO, USA); Digiwalker Caltrac™ (Torence, CA, USA); Tritrac™ (Hemokinetrics, Inc., WI, USA); Tracmor™ (Maastricht, The Netherlands) | 45,53,61-71 83-87 |
| Combined systems | NA | NA | NA | Verify that elevations in heart rate are representative of responses to physical activity | Lack of validation studies; no commercial systems available on the market | | 88 |

a When describing cost estimates, it is important to consider the consumable and investment cost of each device. For example, the cost for a stationary or portable indirect calorimetry system may be up to $US60 000 (2002 values); however, if maintained correctly, one would expect around 1000–2000 tests of 1–9 hours over a 10-year period. As shown, the cost for the DLW dose and analysis for one individual will be approximately $US1000–1250. Therefore, whilst the consumable cost of an indirect calorimetry set-up may be far higher than the DLW, it represents a reusable investment over time. The similar concepts hold for both heart rate monitors and motions sensors, where it is possible to do many measurements after one monitor has been purchased.

**DLW** = doubly labelled water; **EE** = energy expenditure; **FQ** = food quotient; **NA** = data not available.

ometer unit).[83] Thirdly, on a treadmill, Tracmor™ output has been demonstrated to correlate well with EE (r = 0.95).[87] Finally, with respect to detecting body motion, Tracmor™ output correlates well with daily EE (measured using DLW) divided by basal metabolic rate in free-living individuals (r = 0.73; $p < 0.001$).[71,97] Initially, the Tracmor™ unit could not be worn in the water; however, more recently, simple modifications to the device have enabled it to become fully versatile in water. Unfortunately, at present, the Tracmor™ is not yet available on the commercial market.

Levine et al.[72] recently validated the Tracmor™ triaxial accelerometer system for walking. The results showed that the Tracmor™ can be used to predict the energetic cost of walking, provided that separate regression equations are derived for each individual to convert Tracmor™ output to EE. Similar to the use of HR, a calibration curve based on simultaneous measurements of Tracmor™ output and $\dot{V}O_2$, measured using indirect calorimetry, is required for each individual to increase its accuracy in estimating EE. However, the importance of individual calibration curves for the Tracmor™ device is relatively minor compared with that of HR monitors (Westerterp KR, unpublished observations). When tested on an increased gradient, the Tracmor™ failed to detect the increased energetic cost of walking on a steep incline. Utilising a different type of triaxial accelerometer Terrier et al.[98] provided similar results to that of Levine et al.[72] as the device failed to predict the energy cost of uphill or downhill walking when compared with indirect calorimetry measurements.

In contrast to the Tracmor™ device, to our knowledge, there seems to be few validations of the Tritrac™ against DLW,[53] whereas it has been extensively compared with indirect calorimetry measurements.[68,69,99-104] In a recent study, the Tritrac™ underestimated 7-day EE by 35% when compared with the DLW method.[53] Studies comparing the Tritrac™ against short-term measurements of indirect calorimetry have produced very variable results. For example, the Tritrac™ has been shown to underestimate EE significantly in most[69,99-103] but not all[68,102,104] studies where large overestimations in various activities have been reported.

In summary, it seems fair to conclude that, at present, care should be taken when using motion sensors based on accelerometry to predict free-living EE. Moreover, motion sensor data are perhaps best analysed as counts, as there may be significant error with the prediction of free-living EE.[60] By using new algorithms for analysing the acceleration signal in the three axes, such as parameterisation and neural network analysis, slope and walking speeds can be predicted directly, as recently demonstrated by Aminian et al.[105] and Herren et al.;[106] these may be beneficial in the prediction of EE.[107] Another promising area for improving EE prediction in free-living conditions would be the development of an additional tool for assessing the slope by independent methods (such as an altimeter or differential global positioning systems).[107,108] Finally, despite the limitations of motion sensors in predicting EE, they still provide an excellent means to evaluate interventions aimed at increasing physical activity, in an unlimited population range.

### 2.7 Combined Heart Rate and Motion Sensors

To date, there is a limited amount of research on the combination of both HR and motion sensors. The principle is to use a motion sensor as a back-up measure to verify that elevations in HR are representative of responses to physical activity. Such combinations may cut down on the variability of HR alone, due to intervening factors in estimating EE. To our knowledge, only one group[88] has used a one-piece instrument that is able to measure both HR and movement. Previous studies have used separate instruments to record these two measurements.[6,109-112] The results of this preliminary study by Rennie and coworkers[88] showed near perfect agreement in the calculation of EE, when compared with direct measurement of room calorimetry, highlighting its ability to estimate EE and the pattern of EE activity throughout the day. Further validations in free-living individuals, against DLW, are necessary.

 

## 3. Evaluation and Practical Recommendations on the Estimation of EE

Of all the methods for the assessment of EE reviewed, each has a number of positive and negative aspects. Although, the DLW is considered the 'gold standard' method against which other methods are to be validated, the price of the DLW and the sophisticated analysis involved make it impractical for use with large groups.

Indirect calorimetry provides an accurate method of measurement of both EE and respiratory gas exchange both in the laboratory and in the field; however, the nature of the equipment limits usage to less than 8 hours. In addition, the expense of such portable systems limits the measurement to the individual level.

HR monitoring is an objective method of estimating EE. However, HR is affected by more factors than physical activity alone. Ideally, data conversion needs individual measurements of HR in combination with $\dot{V}O_2$, and HR monitors are not well tolerated by individuals for time intervals representative of daily life for 1 week or more. HR monitoring remains a proxy measure for physical activity.[27]

Positive aspects of questionnaires, like the Baecke questionnaire, are the short time needed for an individual to complete the 21 questions, the simple scoring system for the calculation of an activity index and the coverage of the individual's normal daily pattern. A disadvantage of questionnaires is the fact that individuals can easily overestimate or underestimate the time spent in activity, and most questionnaires are not applicable for all individual categories from children, people with and without jobs, to the elderly.[13]

Motion sensors yield objective data, although their estimation of EE, compared with the DLW, is variable. The majority of the recent research seems to show how effective they are becoming in the measurement of physical activity and EE. Perhaps the future in estimating EE lies in the use of a combination of both motion sensors and HR monitoring. Such combinations are recommended to confirm that the elevated HR is representative of responses to physical activity. This combination may provide a more precise means of estimating EE than can be gained from HR or motion data alone. At present, the information about, and validation of such techniques are lacking. Future research needs to target the design of such a combined device.

## 4. Conclusions and Recommendations

The preferred method to determine EE is likely to principally depend on factors such as the number of individuals to be monitored, the time period of measurements and the finances available. Small study participant numbers over a short period may be measured accurately by means of indirect calorimetric methods (stationary and portable systems). For periods over 3–4 days, EE should ideally be measured using the DLW method. However, the use of motion sensors is very promising in the measurement of EE, and has a number of advantages over the DLW method. Furthermore, if used correctly, both HR and questionnaire methods may provide valuable estimates of EE. Additional studies are needed to examine the possibility of improving the accuracy of measurement by combining two or more techniques. Importantly, despite some strong correlations between the DLW gold-standard method and other estimation methods, care should be expressed in the interpretation of these data as strong bivariate relationships do not necessarily imply agreements between the two methods.[56-58] Ideally, future comparative studies should correctly compare their data in terms of 'limits of agreement'. The accurate measurement of physical activity and EE is critical for determining current levels of physical activity, monitoring compliance with physical activity guidelines, understanding the dose-response relationship between physical activity and health and determining the effectiveness of intervention programmes designed to improve physical activity levels.

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Correspondence and offprints: *Philip N. Ainslie*, Department of Physiology and Biophysics, Faculty of Medicine, University of Calgary, Heritage Medical Research Building, Room 209, 3330 Hospital Drive NW, Calgary, Alberta, T2N 4N1, Canada.
E-mail: painslie@ucalgary.ca

 