Comparison of heart rate monitoring combined with indirect calorimetry and the doubly labelled water ($^2$H$_2^{18}$O) method for the measurement of energy expenditure in children


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Summary. The aim of the present study was to compare data on 24-h energy expenditure (EE$_{24\text{h}}$) in nine boys and ten girls (mean age 9.3 and 8.1 years, respectively) by heart rates ($f_c$) combined with energy expenditure obtained from a 1-day stay in an indirect calorimeter (EE$_{ind}$) and a 2-week period of normal living using the doubly labelled water method (EE$_{dlw}$). Individual calibration curves were derived from $f_c$ and oxygen uptake measured during sleep (in the calorimeter), standing and walking on a treadmill. An estimation of energy expenditure based on 24-h $f_c$ monitoring (EE$_{fc}$) was made during the stay in the calorimeter and on a normal school-day. Mean results showed an overestimation in EE$_{fc}$ compared to EE$_{ind}$ and EE$_{dlw}$ of 10.4% and 12.3% respectively, varying from 6.3% to 16.2%. These results confirmed earlier observations in adults that for a group the $f_c$ method overestimates EE$_{24\text{h}}$ by about 10%.

Key words: Energy expenditure – Child – Heart rate method – Indirect calorimetry – Doubly labelled water

Introduction

In recent years there has been a surge of interest in the triad: child – physical activity – health. A major impetus for such interest has been the increasing involvement of children in advanced level athletics. But also the relevance of physical activity in clinical paediatrics has been gaining increasing attention, be it in diagnosis, prevention, management or etiology (Bar-Or 1983).

Measuring daily physical activity in children is one of the most difficult tasks for the physiologist because of the presence of contradictory aims: on the one hand it is desirable to record the normal daily movements of a child, which usually means that the child must be burdened with equipment for measuring a number of body functions. On the other hand, the child’s normal daily activities should not be hindered (Saris 1986).

Of all physiological variables, heart rate ($f_c$) is one of the easiest to measure with the least inconvenience to the subject, especially with the new developments in microelectronics. Therefore, monitoring $f_c$ has become one of the most commonly employed methods in activity studies in children (Saris 1986).

There are, however, certain disadvantages in using this method of prediction: the relationship between $f_c$ and oxygen uptake ($V_{O_2}$) is dependent upon the type of exercise and, furthermore, the relationship is less accurate at low levels of physical activity (Acheson et al. 1980; Christensen et al. 1983; Dauncey and James 1979; Washburn and Montoye 1986).

These disadvantages have been established in adults. However, in children data are scarce and it is suggested that because of the relatively higher activity levels in this age group, $f_c$ monitoring could give a more accurate prediction of the energy expenditure (EE).

The aim of the present study was to compare $f_c$ monitoring with the accurate indirect calorimeter and doubly labelled water method for the measurement of 24 h energy expenditure (EE$_{24\text{h}}$) in children.

Methods

Subjects. Healthy children between 7 and 11 years of age were recruited by using posters and making personal approaches. Parents of 22 children gave their informed consent. In the course of the study it was established that it was impossible to collect data using standard procedures in the indirect calorimeter for 3 of the children (home-sickness). Therefore these children were excluded from further analysis. The study was approved by the Medical Ethics Committee of the University of Maastricht.

Procedure. Body mass, height and thickness of four skinfolds (over triceps, biceps, subcapular and suprailiac muscles) were measured. Percentage body fat was calculated according to the method of Durin and Rahaman (1967).

Three different methods were used to quantify EE$_{24\text{h}}$:

1. A 24 h stay in an indirect calorimeter (EE$_{ind}$).
2. A 14-day measurement using the doubly labelled water method (EE$_{dlw}$).
3. An estimation of EE based on 24 h $f_c$ monitoring (EE$_{fc}$).
**Indirect calorimeter.** To measure EE_{24h} accurately (error less than 2%), 24 h measurements were carried out in an open-circuit indirect calorimeter (14 m³; ventilation rate about 40 l/min⁻¹). Values of the outgoing air were determined by means of a dry gas meter (Sclumberger, Dordrecht, The Netherlands) and gas analysis was made with a paramagnetic O₂-analysing (Servomex, Crowborough, England) and an infrared CO₂ analyser (Hartman and Braun, Frankfurt, FRG). An on-line micro computer controlled the gas sampling system and calculated EE_{cal} automatically according to the equation of Weir (Schoffen et al. 1984): \( E (\text{keal}) = 3.9 \times O_{2} [l] + 1.1 \times CO_{2} [l] \).

The calorimeter was equipped with bed, washstand, toilet, telephone, intercom and TV. Air temperature was maintained at 20°C during the day and at 18°C during the night. Food was offered ad libitum according to the normal diet at fixed times. To make the daily programmes as uniform as possible, activities such as board games, drawing, etc. were scheduled.

**Doubly labelled water.** A representative sample with regard to age and body composition of 10 children (5 boys and 5 girls) was selected from the total group to study EE_{24h} with the EE_{de} method (Lifson and McClintock 1966). An individually calculated dose, which was expected to give an excess of about 350 ppm ¹⁸O and about 265 ppm ³H in the body water, was administered orally to these children in the evening, after collecting a baseline urine sample.

Further urine samples were collected in the morning on day 1 after the first voiding and in the evening at 19 h on day 1, 7, 8, 14 and 15, respectively.

Determination of the isotopic abundances of ²H and ¹⁸O was carried out with an Isotope Ratio Mass Spectrometer (Aqua Sira, VG Isogas, Middleton, Cheshire, England). Mean EE_{de} over 14 days was calculated using an estimated fixed respiratory quotient (RQ) of 0.85 and the equation (Schoeller et al. 1986):

\[ n_{CO_{2}} = \left( \frac{1.01. k_{e} - 0.14. k_{b}}{2.078} \right) - 0.0264 \cdot T \cdot \text{mean} \]

where:

- \( n_{CO_{2}} = \) CO₂ production rate (mol·day⁻¹)
- \( N = \) total body water (mol)
- \( k_{e} = \) elimination rate
- \( k_{b} = \) elimination rate
- \( r_{e} = \) correction factor for evaporative water loss

Estimated by formula \( T = 1.05 \cdot N \cdot (k_{e} - k_{b}) \).

**Heart rate.** The use of the \( f_{e} \) to estimate EE_{24h} was based on the assumption of a close individual linear relationship between \( f_{e} \) and \( V_{O_{2}} \) and thus also between \( f_{e} \) and EE (Bradfield 1971). The \( f_{e} \) - \( V_{O_{2}} \) regression line has been shown to be curved in its lower part up to the so-called transition point and linear in the higher range of \( V_{O_{2}} \).

In this study, two individual regression equations were determined for each subject: for quiet activities (\( f_{e, \text{quiet}} \)) were derived from \( f_{e} \) and \( V_{O_{2}} \) measured during sleep (in the calorimeter) and standing; for dynamic activities \( f_{e} \) and \( V_{O_{2}} \) were measured during five submaximal exercise intensities on a treadmill (Quinton Cardio Exercise, Quinton Instrument CO, Seattle, USA) (\( f_{e, \text{submax}} \)). The transition point was calculated as the mean \( f_{e} \) during standing.

The \( f_{e} \) was measured continuously during the 24-h stay in the calorimeter and simultaneously with the measurement of EE_{de} during 1 school day (0800-1900 hours) by means of a Sporttester PE 3000 (Polar Electro KY, Kempele, Finland). To obtain 24 h \( f_{e} \) values during the school day, \( f_{e} \) values of the remaining resting/sleeping hours (1900 hours to 0800 hours) in the calorimeter were used.

The \( V_{O_{2}} \) was calculated from mean \( f_{e} \) per hour using the two individual regression equations (\( f_{e, \text{quiet}} \) and \( f_{e, \text{submax}} \)). The EE_{de} was calculated from \( V_{O_{2}} \) using an energy equivalent of 20.50 J·l⁻¹·min⁻¹.

**Statistical analysis.** Comparisons between data were made using the Student’s \( t \)-test for paired and unpaired groups (\( \alpha = 0.05 \)).

**Results.** Physical characteristics of the 19 children are given in Table 1. The group corresponds well with the national growth tables (Roede and Van Wieringen 1985). Although there are no reference values available regarding organized sports activities in The Netherlands, there were no indications that the sports activities of this group differed from the norm.

The mean daytime \( f_{e} \) during a schoolday was significantly higher (\( P<0.05 \)) compared to the stay in the calorimeter (Table 2). No statistical differences were observed between the boys and the girls.

Figure 1 shows \( V_{O_{2}} \) plotted as a function of \( f_{e} \) and the mean regression equations (\( f_{e, \text{cal}} \) and \( f_{e, \text{de}} \)) of the 9 boys and 10 girls.

Figure 2 gives mean EE_{24h} of both boys and girls during the stay in the calorimeter, based on EE_{cal} and the \( f_{e} \)-method (EE_{cal} \( f_{e} \)).

The activities in the calorimeter consisted mainly of lying, sitting and standing. However, in 12 of the 19 children \( f_{e} \) values were measured above the individual transition point. Since \( f_{e, \text{cal}} \) represents the activities in the calorimeter, EE_{24h} of all the children was also calculated using only \( f_{e, \text{cal}} \) (EE_{cal} \( f_{e, \text{cal}} \)) for the whole measured \( f_{e} \)-range.

The EE_{24h} based on the two equations (EE_{cal} \( f_{e, \text{cal}} \) + EE_{de}) was significantly higher (\( P<0.05 \)) than EE_{24h} measured by EE_{cal}. No significant difference was found using only \( f_{e, \text{cal}} \). There were no significant differences in EE_{24h} between boys and girls.

Mean EE_{24h} of the selected boys (\( n = 5 \), mean age 8.4 years, body mass 27.8 kg, body fat 13.5%) and girls

**Table 1. Characteristics of the 19 children**

<table>
<thead>
<tr>
<th>Sex</th>
<th>( n )</th>
<th>Age (year)</th>
<th>Height (cm)</th>
<th>Body mass (kg)</th>
<th>Body fat (%)</th>
<th>Sports (min·week⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boys</td>
<td>9</td>
<td>3.9</td>
<td>138.8</td>
<td>30.9</td>
<td>14.2</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4</td>
<td>8.8</td>
<td>4.3</td>
<td>2.2</td>
<td>104</td>
</tr>
<tr>
<td>Girls</td>
<td>10</td>
<td>8.1</td>
<td>132.3</td>
<td>28.2</td>
<td>19.9</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3</td>
<td>6.0</td>
<td>2.6</td>
<td>4.0</td>
<td>31</td>
</tr>
</tbody>
</table>

**Table 2. Mean heart rate in beats·min⁻¹ of 19 children during a stay in a calorimeter and on a schoolday**

<table>
<thead>
<tr>
<th>Sex</th>
<th>Calorimeter (3-6 h)</th>
<th>Calorimeter (8-19 h)</th>
<th>School (8-19 h)</th>
<th>( P^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{mean} )</td>
<td>SD</td>
<td>( \text{mean} )</td>
<td>SD</td>
<td>( \text{mean} )</td>
</tr>
<tr>
<td>Boys</td>
<td>9</td>
<td>75</td>
<td>9</td>
<td>93</td>
</tr>
<tr>
<td>Girls</td>
<td>10</td>
<td>85</td>
<td>11</td>
<td>107</td>
</tr>
</tbody>
</table>

* \( P \), Significance level of difference between daytime heart rate in the calorimeter and during a routine schoolday

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1 Error in estimation of EE by fixed RQ is 1% for each 0.01 unit RQ
Fig. 1. Mean oxygen uptake (\(\dot{V}O_2\)) as a function of heart rate (f) during quiet activities (Q), sleeping and standing) and dynamic activities (dyne, five submaximal exercise intensities on a treadmill) in boys (n = 9) and girls (n = 10).

- Boys: \(f_{0.5\text{BQG}}\): \(\dot{V}O_2 = 4.663f_0 - 169.837\)
- Girls: \(f_{0.5\text{BQG}}\): \(\dot{V}O_2 = 12.439f_0 - 829.985\) \(r^2 = 0.977\)

Fig. 2. 24-h Energy expenditure (EE_{24h}) in the calorimeter (mean and SD) of 19 children based on indirect calorimetry (EE_{cal}) and predicted from heart rate (f) recording using one regression equation (EE_{cal/f0,BQG}) or two regression equations (EE_{cal/f0,BQG} + EE_{dyne})

(n = 5, mean age 8.4 years, body mass 28.3 kg, body fat 20.2%) during a school period is given in Fig. 3. The EE during the schoolday (0800–1900 hours) was calculated from \(f_0\) using both regression equations. The EE during the night (1900–0800 hours) was calculated from \(f_0\) in two ways:

1. Using both \(f_0\text{BQG}\) and \(f_0\text{BQG}_{dyne}\) (EE_{school/f0,BQG} + EE_{dyne})
2. Using only \(f_0\text{BQG}\) (EE_{school/f0,BQG})

No statistical differences could be observed between EE_{24h} and the predicted EE from \(f_0\) with any regression equation. However, EE_{school/f0} was on average about 14.5% higher. Despite the fact that the boys had about an 8% higher EE_{24h}, compared to the girls, this difference was not statistically significant.

**Discussion**

To investigate whether the \(f_0\) method is suitable to estimate daily physical activity in children, \(f_0\) monitoring was carried out during a 24-h stay in an indirect calorimeter and during EE measurements by means of the doubly labelled water technique during a normal school period of 14 days.

Using indirect calorimetry, EE can be measured accurately (error less than 2%; Karlberg 1952). The application of the indirect calorimeter is however limited because it is not possible to measure in normal-living conditions. The EE_{cal} is therefore not representative for daily EE in children.

The doubly labelled water technique is very well suited to measuring the EE of children under normal daily living conditions over longer periods of time (14 days), because the inconvenience is minimised to just drinking a glass of water and the collection of some urine samples. Recently Westerterp et al. (1988) have reported on the validation of this method using respirometry at low and high levels of activity. At the low level of activity EE from the doubly labelled water method was on average 1.4 (SD 3.9) % higher than from respirometry; at the high level of activity, the doubly labelled water method yielded values that were 1.0 (SD 7) % lower than those from respirometry. From these results it could be concluded that the method could measure EE with reasonable accuracy over the range of activity levels found in daily life. However, for routine studies the method is not suitable because of the relatively high cost of a single dose of doubly labelled water. Therefore, the
doubly labelled water technique is an excellent method to serve as a reference value to validate other EE field techniques.

The method is considered to be a good indicator of EE. It is a relatively cheap method and causes little inconvenience to the subject (Astrand and Rodahl 1986; Bar-Or 1983). However, at low levels of physical activity, the prediction of EE from \( f_c \) has been found to be inaccurate because of the influence of several factors (emotion, posture, ambient temperature) on the measured relationship between \( f_c \) and \( \dot{VO}_2 \). The influence of these factors on the EE estimates makes the applied procedure unsuitable for studies of individual subjects who engage in ordinary daily activities with an average 24 h \( f_c \) only slightly above their resting \( f_c \) (Christensen et al. 1983). Dauncey and James (1979) have reported a mean overestimation in EE from \( f_c \) of 3%–16% (SD 10%–15%) in a whole-body calorimeter with low activity levels. In a study carried out by Washburn and Montoye (1986), in which the validity of the \( f_c \) method was assessed, the best calibration method led to a mean overestimation of 12%, varying from −31% to +45%. Recently, Livingstone et al. (1990) have reported on the discrepancies in EE calculated from the Flex \( f_c \) method and the doubly labelled water technique in 14 adults. Predicted EE from \( f_c \) discrepancies ranged from −22.2% to +52.1% with nine values lying within ± 10% of EE_{dwy}.

The aim of the present study was to assess the accuracy of the \( f_c \) method in children. Data on EE_{24h} predicted from \( f_c \) were therefore compared to EE calculated from indirect calorimetry and doubly labelled water. The percentage differences between actual and predicted EE_{24h} are shown in Fig. 4.

The use of both regression equations (columns 1, 3) resulted in considerably larger overestimations than calculations using only one. These results confirmed observations made on adults (Saris 1982) that the activity to calibrate the relationship between \( f_c \) and \( \dot{VO}_2 \) for individuals should be as close as possible to the actual physical activities to be measured.

Because of the relatively higher level of physical activity in children, it was suggested that \( f_c \) monitoring could give a more accurate prediction of EE in this age group than in adults. However, the results of this study did not confirm this hypothesis. As shown in Fig. 4 (columns 2, 4), the \( f_c \) method in children resulted, in comparison with the indirect calorimetry and the doubly labelled water method, in mean overestimations in EE_{24h} of 10.4% and 12.3% respectively, varying from 6.3% to 16.2%. This was in agreement with the results found for adults.

Noteworthy is the observed higher overestimation in the boys during a school day compared to the girls, although the boys were more active. This was possibly the result of differences in the response of \( f_c \) and \( \dot{VO}_2 \) when changing from one level of activity to another as shown by Saris (1982). Predicted EE of less intense activities was considerably overestimated when they followed more intense activities. Especially in boys where possibly more frequent short bursts of intense exercise were followed by rest, this phenomenon could have contributed to the overestimation.

However, in comparison with the inconvenience of the calorimeter and the expense of the doubly labelled water technique, \( f_c \) monitoring would seem at present to be the most suitable method for use in large scale activity studies on children to predict EE for groups. The method would, however, be of little value in predicting EE for individuals.

References


![Fig. 4. Mean and SD percentage differences between actual and predicted EE_{24h}. For other definitions see Figs. 2 and 3](image-url)