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Original article

Comparison of heart rate monitoring with indirect calorimetry for energy expenditure evaluation

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Abstract

Purpose: The purpose of this study was to compare established methods with newly-developed methods for estimating the total energy expenditure (TEE).
Methods: The study subjects comprised 46 individuals, including 16 middle-aged men (mean age 51.4 years), 14 middle-aged women (mean age 49.9 years) and 16 young women (mean age 19.1 years). The TEE was estimated from 24-h heart rate (HR) data using newly-developed software (MoveSense HRAnalyzer 2011a, RC1, Suunto Oy, Vantaa, Finland), and was compared against the TEE determined using doubly labeled water (DLW). Agreement between the two methods was analyzed using Bland and Altman plots.
Results: The HR method yielded similar TEE values as the DLW method at the group level, with an average of 8.6 kcal/day in the difference in the mean, but with large individual variations. Forty-four (96%) out of 46 subjects fell within ±2SD of the mean difference in TEE comparisons, and there was no tendency towards under- or over-estimation.
Conclusion: Our results indicate that the current software using HR analysis for the estimation of daily TEE needs further development for use with free-living individuals.

Keywords: Doubly labeled water; Heart rate monitoring; Males and females; Total energy expenditure

1. Introduction

The assessment of energy expenditure in free-living subjects is central to investigations in the etiology of obesity, malnutrition, coronary heart disease, osteoporosis, and other chronic diseases.[1−5] As a result, a number of techniques for assessing energy expenditure have been devised. Total energy expenditure (TEE) is comprised of three main components: the basal metabolic rate or resting energy expenditure (REE), diet induced thermogenesis, and the energy expended in physical activity.[6] The doubly labeled water (DLW) technique is considered as the gold standard for measuring the TEE under free-living conditions, and is particularly useful for

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measuring the average metabolic rate over a relatively long period of time (7 days or 2 weeks). However, this method is used mostly in small study populations due to the expensive cost. In recent years, several methods with acceptable accuracy have been proposed as alternatives such as heart rate (HR) monitoring and whole body composition to the DLW method.[7–16]

HR monitoring has emerged as another way to estimate the TEE based on the well-established relationship between HR, oxygen uptake and energy consumption.[17–19] HR monitoring has also been used to evaluate the level of physical activity.[2,9,11,19–21] In large population-based studies, HR monitoring is one of the most efficient and economical means of estimating free-living energy expenditure. It also provides useful insights into the intensity of the physical activity being undertaken over the measurement period.[13] However, the HR monitoring duration is limited by the data storage capacity of the device used.[17] The validation of HR for measuring the TEE has been performed mostly via VO_2 testing during high intensity exercise, and few studies have compared high intensity versus low intensity exercise.[11,13,19,22]

Due to advances in technology and the development of revised software, not all newly-developed devices have been compared to well-established, conventional standards, such as the DLW method, for estimating the TEE. The objective of this study was to compare TEE estimates from the new HR analysis algorithm developed by Suunto Company with that from the DLW method in healthy young females and middle-aged females and males.

2. Subjects and methods

2.1. Subjects

Fifty-five male and female subjects volunteered to participate in the DLW assessments to estimate their TEE. Six subjects were excluded from this report because of anomalies in their ^2H and ^{18}O decay curves. An additional three subjects were excluded because of missing HR logs. The final sample of 46 subjects included 16 middle-aged men (mean age 51.4 years), 14 middle-aged women (mean age 49.9 years) and 16 young women (mean age 19.1 years). This study was conducted in accordance with the Helsinki Declaration, and was approved by the ethics committee of the Central Finland Health Care District. Written informed consent was obtained from all subjects prior to the assessments.

2.2. Anthropometric measurements

All measurements were performed after an overnight fast. The participants were weighed while wearing light clothes and without shoes. The weight was determined within 0.1 kg for each subject using an electronic scale calibrated before each measurement session. The height was determined using a fixed wall-scale measuring device to the nearest 0.1 cm. The body mass index (BMI, kg/m^2) was calculated as weight/height^2.

2.3. Energy expenditure assessment by indirect calorimetry

2.3.1. DLW method

The TEE (kcal/day) was measured by the DLW method as previously described.[23] Briefly, on day 1, the first urine sample was collected from each participant in the morning before the intake of a body weight-dependent (1 g per kg of body weight) dose of DLW (pre-mixed aliquots of 100 g of 10% ^{18}O enriched water with 8 g of 99.9% ^2H enriched water). Four to six hours after consuming the DLW, the subjects provided a second urine sample. On day 14, the first sample was obtained in the morning after an overnight fasting, and the second sample was collected 4–6 h afterwards. The urine samples were stored at −80 °C until analysis. The samples were analyzed in triplicate for the ^2H and ^{18}O isotope ratio by mass spectrometry (Metabolic Solutions Inc., Merrimack, NH, USA) at the University of Alabama, Birmingham, USA. The TEE was calculated using the validated described by Schoeller et al.[24,25]

2.3.2. HR monitoring

The subjects wore an HR monitor (Body Guard, FirstBeat Oy, Jyväskylä, Finland) for 24 h before the REE measurement. The device was attached directly to the skin at three points, eliminating the need to wear a belt around the body and thus minimizing skin contact. The recorded 24-h HR data were then downloaded to a computer. The TEE was estimated using newly-developed software (MoveSense HRAnalyzer 2011a, RC1) provided by Suunto Company (Vantaa, Finland). The algorithm used in this software for the TEE estimation is based on HR reserve, taking into account age, gender and BMI.

2.3.3. Respiratory gas exchange analysis

The REE (kcal/day) was assessed by respiratory gas exchange analysis (GEA) using a ventilated-hood system (VIASYS Healthcare, Yorba Linda, CA, USA). Calibration of the GEA was carried out before each measurement according to the manufacturer's instructions. The subjects were instructed to avoid any strenuous physical activity for 24 h before the laboratory visit. They were transported to the laboratory by car after an overnight fast. After relaxing in a bed for 30 min, a ventilated hood was placed over their heads. Their oxygen consumption and carbon dioxide production were measured for 20 min at 1 min intervals, in a supine position in a thermoneutral (22–24 °C) environment. The first 5 min of the data were discarded as artefacts. The REE was calculated using the modified Weir equation.[26]

2.3.4. Bioimpedance assessment

An Inbody 720 bioimpedance device (Biospace, Co, Ltd, Seoul, Korea) was used to assess the body composition immediately after the respiratory gas exchange assessment. The REE values were automatically calculated and exported by the device. The REE estimation is based on the measured fat-free mass (FFM) and the equation developed by Cunningham[27]: $REE = 21.6 \times FFM\ (kg) + 370$.

2.3.5. Harris—Benedict equation

The REE was also calculated using the original Harris—Benedict equation[28]: for men, REE = 66.5 + 13.75 × weight (kg) + 5.003 × height (cm) − 6.775 × age; for women, REE = 655.1 + 9.563 × weight (kg) + 1.850 × height (cm) − 4.676 × age.

2.4. Statistical analysis

All data were checked for normality by Shapiro—Wilk's *W*-test. Paired *t* test or analysis of variance (ANOVA) with least significant difference (LSD) *post-hoc* test were used to evaluate the differences in the TEE and REE values obtained by the different estimation techniques. The correlations between the different TEE and REE methods were evaluated by Pearson correlation coefficients. The TEE and REE values obtained from different methods were also compared using Bland and Altman analysis.[29] Linear regression analysis with a stepwise method was used to assess whether the differences between the tested methods were influenced by age, gender or BMI of the subjects. STATISTICA for Windows v9.0 software (StatSoft Inc., Tulsa, OK, USA) was used to perform all statistical analyses. A p value less than 0.05 was considered statistically significant.

3. Results

The basic characteristics of the study subjects are presented in Table 1. There were no significant differences in age between the middle-aged women and men. As expected, the men were on average 11 and 8 cm taller and 15 and 13 kg heavier, and had more FFM, than the young and middle-aged women, respectively (all $p < 0.01$). No significant differences were observed in the BMI among the groups.

The energy expenditure estimates obtained from DLW and HR monitoring are presented in Table 2. No significant differences in the TEE estimates were found between the DLW and HR methods across age and gender groups.

There were significant correlations between the TEE measured by DLW and the values estimated by HR ($r^2 = 0.42$, $p < 0.001$, Fig. 1A). Linear regression analysis showed that individual differences in the TEE estimates between the HR analysis and the DLW method were not affected by age, gender or BMI ($p > 0.05$). The agreement (all within ±2SD of the mean difference) between the different methods was assessed by the Bland—Altman method, and the results are shown in Fig. 2. Both DLW and HR analyses yielded similar results for the TEE, with a mean difference of −8.6 kcal/day. Forty-four (96%) out of 46 subjects fell within ±2SD of the mean difference in TEE comparisons, and there was no tendency towards under- or over-estimation.

Since the REE is the largest component of the TEE and different methods and equations have been used to estimate the REE in current years, we included REE estimations in the same subjects as a reference. We found that the GEA, Harris—Benedict equation and Cunningham equation used by bioimpedance assessment (BIA) all yielded similar REE estimates in middle-aged women and men. However, in young women, the Cunningham equation (BIA) gave significantly lower REE estimates than both GEA ($p = 0.006$) and the Harris—Benedict equation ($p = 0.011$)(Table 2). The mean difference between the GEA and Cunningham equation (BIA) was 1.4 kcal/day, and the correlation was $r^2 = 0.64$ ($p < 0.001$, Fig. 1B).

Table 1
Overall characteristics of the subjects (mean ± SD).

	Young women (n = 16)	Middle-aged women (n = 14)	Middle-aged men (n = 16)
Age (years)	19.1 ± 1.2	49.9 ± 5.2	51.4 ± 3.4
Height (cm)	165.0 ± 6.1	168.0 ± 4.3	176.0 ± 6.3*
Weight (kg)	69.2 ± 16.3	71.3 ± 11.1	84.5 ± 12.5*
BMI (kg/m^2)	25.3 ± 5.3	25.8 ± 4.5	27.9 ± 4.3
FFM (kg)	46.6 ± 5.5	48.1 ± 5.1	65.4 ± 9.2*

*$p < 0.01$, compared to young or middle-aged women.
Abbreviations: BMI = body mass index; FFM = fat-free mass.

Table 2
Energy expenditure estimates of the subjects using different methods (mean ± SD).

	Young women (n = 16)	Middle-aged women (n = 14)	Middle-aged men (n = 16)
Total energy expenditure (kcal/day)			
DLW	2111 ± 292	2043 ± 301	2618 ± 423
HR	2129 ± 461	1989 ± 285	2665 ± 441
p value	0.829	0.479	0.634
Basal metabolic rate (kcal/day)			
GEA	1441 ± 124	1390 ± 134	1731 ± 181
Harris—Benedict	1521 ± 156	1415 ± 107	1759 ± 168
Cunningham equation	1373 ± 121	1410 ± 111	1782 ± 199
p value	<0.05	>0.05	>0.05

Note: p values were obtained from a t test or one way ANOVA.
Abbreviations: DLW = doubly labeled water; HR = heart rate.

4. Discussion

In this study we showed that the TEE estimated by HR monitoring compared well with that derived from the DLW method in young women, as well as in middle-aged men and women, but with large individual variations.

HR monitoring is the most popular method for assessing free-living energy expenditure and the patterns of physical activity.[30] It fulfills many of the criteria for providing continuous, indirect, and objective measures of the TEE, being relatively inexpensive, simple to use and non-invasive. The TEE estimation from the HR is based on the fact that under most circumstances, the HR is correlated with the rate of oxygen consumption, and hence the rate of energy expenditure.[31] Unfortunately, the predictive power of HR monitoring as an index of energy expenditure at low levels of activity is poor,[11] particularly in the critical HR range where resting and active conditions converge and overlap.[32] As a result, the HR method for TEE estimation performs well under circumstances

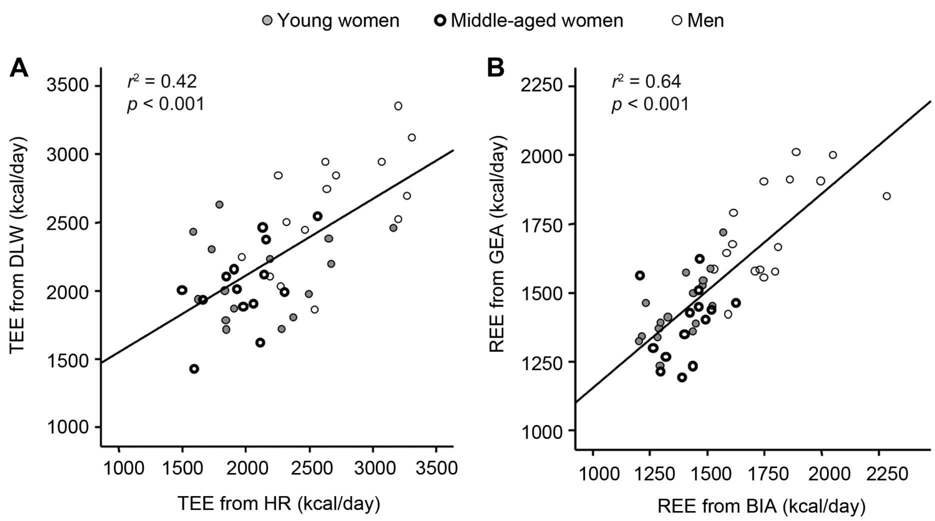

Fig. 1. Pearson correlations between total energy expenditure (TEE) estimates from doubly labeled water (DLW) and heart rate (HR) analysis method (A), and between resting energy expenditure (REE) values from gas exchange analysis (GEA) and the Cunningham equation used by bioimpedance assessment (BIA) assessment (B). The solid line represents the fitted regression line for the total sample.

of moderate to vigorous exercise, but is much less accurate in sedentary people.[8,33,34] To overcome this shortcoming, combining HR monitoring with accelerometry has been suggested to improve energy expenditure estimation.[2] However, a recent study using the Actiheart monitor showed that this combined accelerometry/HR method did not provide any better energy expenditure estimates than using HR monitoring alone.[35]

The accuracy of TEE estimation by HR depends on the accuracy of the manufacturer's proprietary software, namely the algorithm used.[36] In an Australian study using Suunto's previous software, the TEE was underestimated in runners during a submaximal running test when compared to gas analysis data.[37] Livingstone and colleagues[32,38] reported that the mean difference in the TEE obtained from the HR and DLW methods varied between 24 and 98 kcal/day. Likewise in a Japanese study, the HR TEE was also higher by a mean difference of 57 kcal/day in contrast to the DLW method.[39] In addition, Davidson et al.[40] reported that TEE values obtained from HR monitoring were 190 kcal/day higher as compared to DLW. In contrast, Van den Berg-Emons and colleagues[41] found that DLW gave higher TEE values than HR by 17 kcal/day. In the current study, we found that TEE estimated by HR analysis was similar to that assessed by DLW in ordinary males and females. The average difference was only 9 kcal/day, which was better than the above-mentioned studies. Thus, our results indicate that HR analysis using Suunto's software (MoveSense HRAnalyzer 2011a, RC1) can

Fig. 2. Bland−Altman plots for the agreement analysis between doubly labeled water (DLW) and heart rate (HR) analyses for total energy expenditure (TEE) estimation (A), and between gas exchange analysis (GEA) and the Cunningham equation used by bioimpedance assessment (BIA) assessment for resting energy expenditure (REE) estimation (B). Ref (reference) is when the differences between the two methods equal zero. The solid line represents the mean and the broken lines the ±2SD thresholds for the whole sample.

be applied for TEE estimation in a free-living ordinary population at the group level.

The REE is the amount of energy expended by the metabolically active components of the body at rest. FFM accounts for about 65%−90% of the individual variance in REE,[27] and the REE accounts for about 60%−75% of the TEE.[6] The knowledge of the source of the REE and its relationship with the TEE has been used as a basis for establishing effective weight management programs.[42] Substantial efforts have been made to develop age- and gender-specific[28,43−45] or body composition-specific[27,46] equations to estimate the REE. A Swiss study group[47] compared five equations; the Harris−Benedict, Mifflin−St Jeor, Owen, World Health Organization and Lührmann methods, to indirect calorimetry, and found that the mean differences varied between −41 and 53 kcal/day in the elderly. We found mean differences of 25, 28, and 73 kcal/day in middle-aged women, men and young women, respectively, indicating that the Harris−Benedict equation overestimated the REE, especially in the younger female population, as compared to indirect calorimetric GEA. Few studies have validated the Cunningham equation used by BIA against indirect calorimetry.[10,48] We found that there were no significant differences in the REE estimates between GEA and the Cunningham equation used by BIA (InBody 720) among middle-aged men and women. However, the Cunningham equation significantly underestimated the REE in 19-year-old young women. This indicates that the relationship between FFM and the REE is probably age-specific, and the predictive equations derived from adults may not be applicable to younger people.

The major limitation of our study was that the TEE estimation using HR analysis was based on a 24-h recording, whereas the TEE derived from DLW reflects the average daily energy expenditure over 14 days. This is one of the main causes underlying the differences between TEE estimates from HR analysis *vs*. DLW and the large individual variation. However, the variance in TEE estimation between the DLW and HR methods found in our study has also been reported in other studies.[11,16,22,40,49] The HR monitoring has an advantage in monitoring day-to-day energy expenditure, which is important for most practical purposes. Secondly, the subject population was mixed with different genders and ages, which may lead to an underestimation of the agreement between the methods tested.

We conclude that HR analysis using Suunto's software (MoveSense HRAnalyzer 2011a, RC1) needs further development for use in estimations of the daily TEE in free-living individuals.

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