

A new method to estimate energy expenditure from abdominal and rib cage distances

S. Gastinger · H. Sefati · G. Nicolas ·
A. Sorel · A. Gratas-Delamarche · J. Prioux

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Abstract The aim of this paper is to validate a new method of energy expenditure (EE) estimation stemming solely from the measurement of rib cage, abdominal and chest wall distances. We set out to prove that the variations of these distances, measured by two pairs of electromagnetic coils, lead to the estimation of the ventilation (\dot{V}_E) and the EE. Eleven subjects were recruited to take part in this study (27.6 ± 5.4 years; 73.7 ± 9.7 kg). Each subject participated in two tests. The objective of Test 1 was to determine the individual and group equations between the \dot{V}_E and EE during light to moderate activities while Test 2 compared the two pairs of electromagnetic coils with the

indirect calorimetry so as to estimate EE in upright sitting and standing positions and during walking exercises. During Test 2, we compared EE measured by indirect calorimetry ($EE_{IC-Val-REF}$) with EE estimated by the two pairs of electromagnetic coils through the application of: (1) the individual equation ($EE_{mag-Val-INDIV}$) and (2) the group equation ($EE_{mag-val-GROUP}$). The results show that there is no significant difference between $EE_{IC-Val-REF}$ and $EE_{mag-Val-INDIV}$ and between $EE_{IC-Val-REF}$ and $EE_{mag-val-GROUP}$ for each activity. Furthermore, the mean difference seems to show that the estimation of EE is better with the group equation. In conclusion, on the proven basis of this study we are able to validate this new method which permits the estimation of EE from abdominal and rib cage distances. This study also highlights the advantage of using a group equation to the estimate EE.

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S. Gastinger (✉) · G. Nicolas · A. Sorel ·
A. Gratas-Delamarche
Laboratory « Movement, Sport and health Sciences » (M2S):
Physiology and Biomechanics. UFR APS University Rennes 2,
Avenue Charles Tillon, CS 24414, 35044 Rennes Cedex, France
e-mail: gastingersteven@yahoo.fr; steven.gastinger@univ-
rennes2.fr

G. Nicolas
e-mail: guillaume.nicolas@univ-rennes2.fr

A. Sorel
e-mail: anthony.sorel@univ-rennes2.fr

A. Gratas-Delamarche
e-mail: arlette.delamarche@univ-rennes2.fr

H. Sefati
University Rennes 1, 263 avenue Général Leclerc,
CS 74205, 35042 Rennes Cedex, France
e-mail: hamidullah.sefati@gmail.com

J. Prioux
ENS-Cachan, Brittany Branch, Campus of Ker-Lann,
35170 Bruz Cedex, France
e-mail: jacques.prioux@bretagne.ens-cachan.fr

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Rest condition · Exercise condition

Introduction

Physical activity (PA) and increasing energy expenditure (EE) are associated with reduced morbidity and mortality in many chronic diseases including cardiovascular disease, diabetes mellitus, and some forms of cancer (Crespo et al. 1996; Dipietro et al. 1993; Knowler et al. 2002; Manini et al. 2006; Sherman et al. 1994; Tuomilehto et al. 2001; Zinman et al. 2004). The precise measurement of PA is important in characterizing the dose–response relationship between PA and health outcomes (Bouchard 2001), in specifying which dimension of activity is most important and finally in determining possible changes in lifestyle (Goran and Poehlman 1992; Wareham and Rennie 1998).

Therefore, a need for non-intrusive, accurate and valid methods for the measurement of PA and the prediction of EE is justified while addressing important health issues. Furthermore, the self-monitoring of daily EE may increase awareness with regard to the levels of EE needed in the reduction of health problems associated with physical inactivity (e.g., obesity and type 2 diabetes) and serve as a useful element to promote lifestyle changes (Knowler et al. 2002; Tuomilehto et al. 2001; Wierenga et al. 1990).

There are two ways to evaluate PA, either by recording body movements (pedometers and accelerometers) or by measuring their physiological consequences (heat loss, oxygen consumption, and heart rate). Direct calorimetry, indirect calorimetry, and the doubly labeled water method are considered as the most accurate methods to assess PA by measuring heat loss, oxygen consumption or elimination rates of deuterium and oxygen-18 and translating it into EE. However, because of their cost and technical demands, they are limited to small experimental studies. They can, however, be used as criterion methods in validation studies (Fruin and Rankin 2004; Hoos et al. 2003). Current methodologies incorporate the use of portable electronic monitors of motion to objectively quantify PA and EE. Among these devices, accelerometers are becoming increasingly more popular and are often used to predict EE and to classify the levels of PA (Corder et al. 2007a; Montoye et al. 1983; Plasqui and Westerterp 2007). However, pedometers and accelerometers, generally located at the hip, are unable to detect arm movements or for example, exertion during the lifting or pushing of objects. This external work could represent a considerable component of the subject's lifestyle (Bassett et al. 2000).

Heart rate (HR) monitors are valuable tools in the providing valid measurements in comparison to electrocardiograms (Karvonen et al. 1984; Leger and Thivierge 1998; Treiber et al. 1989). Furthermore, since HR is linearly related to oxygen consumption ($\dot{V}O_2$) linked to dynamic activities involving large muscle groups (Christensen et al. 1983; Spurr et al. 1988), it can provide a reasonable estimation of EE during exercise (Ceasay et al. 1989; Eston et al. 1998). Nevertheless, HR could be increased by emotions like anxiety, the rise in body temperature, or as a postexercise response lag without evident-associated increase in EE (Achten and Jeukendrup 2003). The combination of accelerometry with heart rate or heat flux monitoring has increased the accuracy in assessing PA (Corder et al. 2005; Fruin and Rankin 2004; Jakicic et al. 2004; King et al. 2004; Truth et al. 1998). This procedure should, however, be validated and fine-tuned with regard to the specific study populations (Arvidsson et al. 2007, 2009; Zakeri et al. 2008).

Taking into account, and in view of all other existing methods, we set out to develop a new method with the

specific aim of estimating an accurate EE while providing a portable and non-invasive solution. We, therefore, intended to explore pulmonary ventilation (\dot{V}_E) so as to estimate EE. Indeed, two studies have already suggested that \dot{V}_E could be an index of EE (Durnin and Edwards 1955; Ford and Hellerstein 1959). Likewise, Durnin and Edwards suggest the construction of a separate regression line for each subject, using the two variables \dot{V}_E and EE. For these authors, the individual relationships ($EE = f(\dot{V}_E)$) are important to establish because the linear range covers the vast majority of everyday physical activities. Nevertheless, the development of individual relationships for each subject can be restrictive in the estimation of EE on a large population. The development of a group equation could be an interesting solution that would increase the feasibility of our method under daily life conditions.

Given the high correlation between $\dot{V}O_2$ and indirect calorimetry-assessed EE described in the literature (Harrell et al. 2005; Macfarlane 2001; Montoye et al. 1996), the validity of the \dot{V}_E method for estimating $\dot{V}O_2$ (Gastinger et al. 2010b) and the validation of the measurement of \dot{V}_E from two pairs of electromagnetic coils (Gastinger et al. 2010a) (Fig. 1), the aims of our study are: (1) to ensure the validity of electromagnetic coils so as to estimate EE under resting and moderate exercise conditions and (2) to prove the feasibility of our method of estimating EE from the application of a group equation in comparison with the individual equations.

Materials and methods

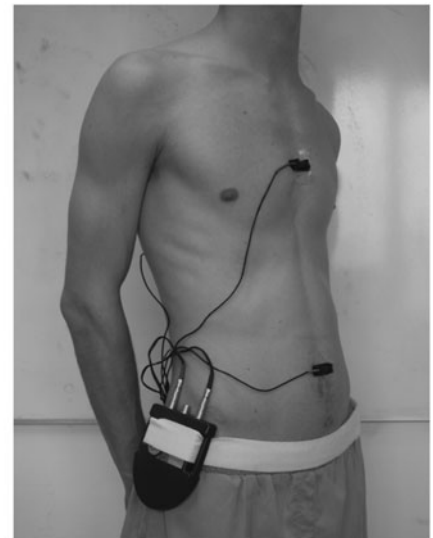
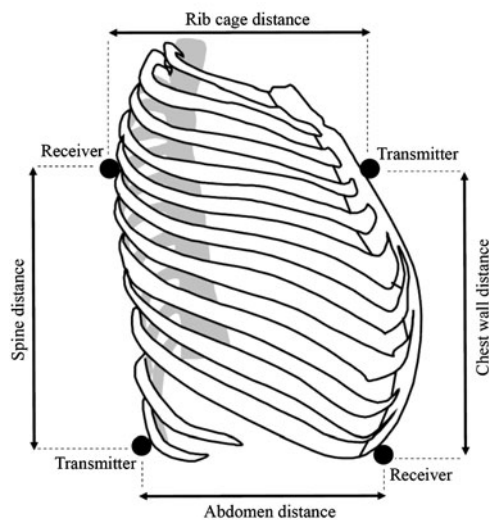
Subjects

Eleven healthy males, aged 27.6 ± 5.4 years, voluntarily took part in this study (height 179.1 ± 5.7 cm, weight 73.7 ± 9.7 kg, fat mass $14.2 \pm 4.02\%$, body mass index 22.9 ± 1.8 kg m⁻²) which was conducted according to the guidelines laid down in the Declaration of Helsinki (1964). All formalities and procedures that involve the participation of human subjects were approved by the local ethics committee of the Université de Rennes 1, France. The subjects were informed of all procedures in writing and written consent was obtained from each. None of the subjects reported respiratory or cardiac disease, or hypertension, or was known to be suffering from any other chronic disease.

Experimental protocol (Fig. 2)

This study required that each subject take part in two tests (Tests 1 and 2) with an interval of 24 h between each test.

Fig. 1 Configuration and placement of the two pairs of electromagnetic coils on the subject



The tests were conducted under controlled laboratory conditions. Each test required that participants refrain from physical activity, medicine, alcohol, and tobacco 24 h before testing and avoid eating up to 2 h beforehand. The subjects were asked to arrive at the laboratory 30 min before the beginning of the measurements.

Test 1

The subjects participated in five successive activities with an interval of 10 min between each at rest in a sitting position. Each subject carried out these five activities in the same order and each activity involved 5 min of measurement to ensure an oxygen uptake ($\dot{V}O_2$) steady state. To confirm the steady state of $\dot{V}O_2$, we verified that during the last minute of exercise $\dot{V}O_2$ varied in the range of $\pm 0.15 \text{ l min}^{-1}$ (Taylor et al. 1955). The first activity to be performed was at rest period in a sitting position. A reference position was maintained by all subjects: back straight, hands on knees, and heels on the ground. The second activity was rest period in a standing position. The reference position applied here was to keep the back straight, arms along the body, and legs apart at shoulder distance. The three activities which followed involved walking exercises on a treadmill at 4, 5 and 6 km h^{-1} . The subjects were instructed to walk in a natural way.

Test 2

This test was composed of a variety of physical activities of various different intensities. These exercises were composed of body posture (sitting and standing) and ambulatory activities (walking at 4, 5, and 6 km h^{-1}). The subjects carried out these activities in a random order and each activity was initialized with a 3 min warm-up period,

followed by 5 min of recording, and was separated by 10 min at rest in a sitting position.

Measurements

Gas exchange measurements

Breath-by-breath measurements of gas exchange were made using an indirect calorimetry (IC) system, the MetaLyser 3B-R2 (Cortex Biophysic, Leipzig, Germany). Expiratory airflow was measured with a volume transducer (Triple V[®] turbine, digital) connected to an O₂ analyzer. Expired gases were analyzed for oxygen (O₂) with electrochemical cells and for carbon dioxide (CO₂) output with the ND infrared analyzer. Before each test, the MetaLyser 3B-R2 was calibrated according to manufacturers' guidelines. After a 60-min warm-up period, the CO₂ and O₂ analyzers were calibrated against room air as well as a reference gas of known composition (5% CO₂, 15% O₂, and 80% N), and the volume was calibrated by five inspiratory and expiratory strokes with a 3-liter pump. Oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$) and ventilation (\dot{V}_{EIC}) were measured and displayed continuously on the computer screen. The entire data ($\dot{V}O_2$ and \dot{V}_{EIC}) during each breath was calculated, and the sampled data transferred breath-by-breath to a PC for real-time display. The recorded data was saved in the internal database of MetaSoft[®] for a precise performance analysis after the test.

Anthropometric data

Height and body weight were assessed by standard anthropometric methods. Fat mass was estimated by the method of skin folds (Harpenden[®] Skinfold caliper).

Experimental protocol : tests 1 and 2

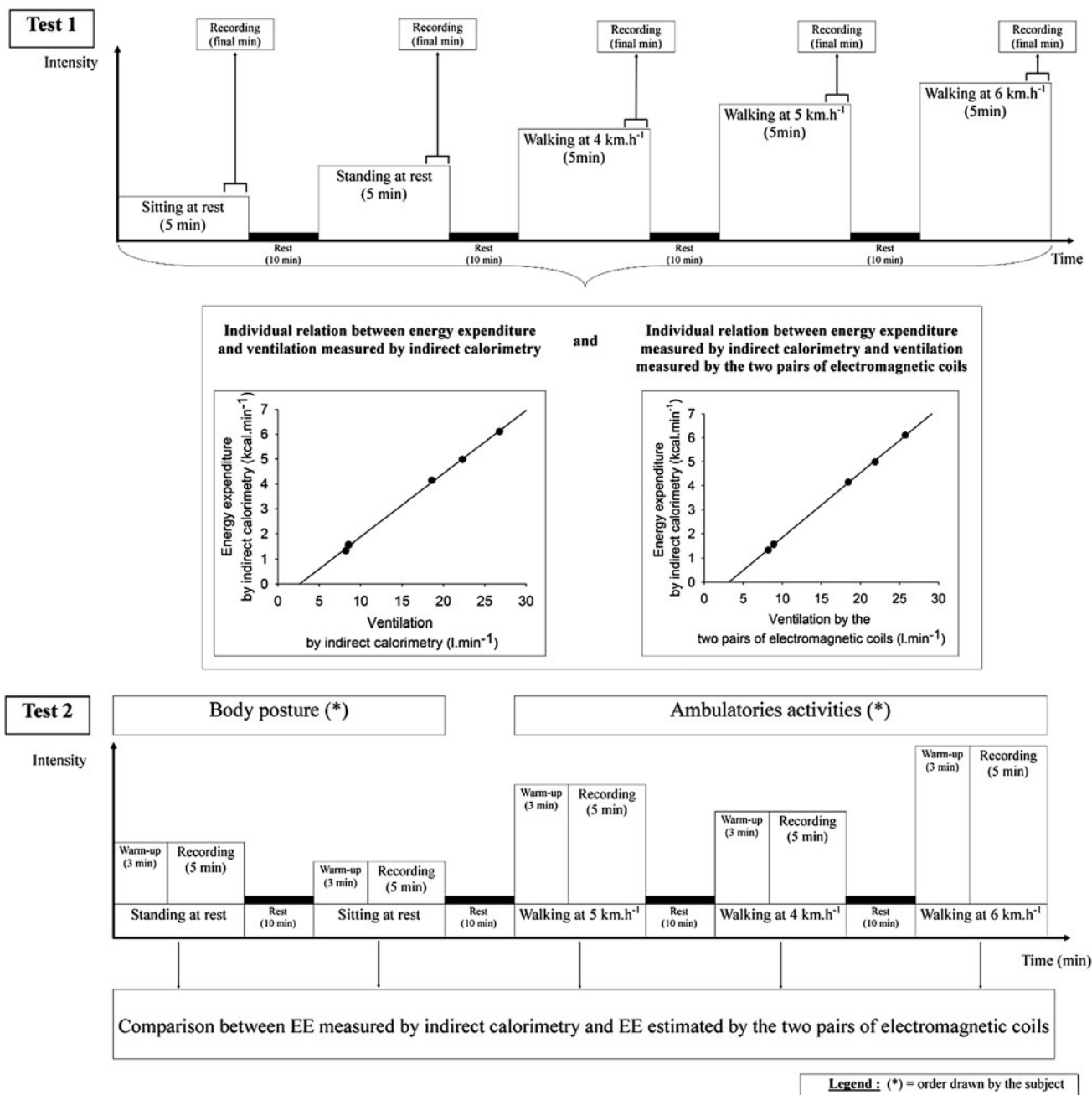


Fig. 2 Details of the experimental protocol (Tests 1 and 2)

Non-invasive method to estimate ventilation

A new device (Nomics-WSL2, Liege Science Park, Belgium) has been developed so as to estimate \dot{V}_E (Gastinger et al. 2010a). This device is made up of two pairs of electromagnetic coils securely connected to a case. One pair of electromagnetic coils is composed of a transmitter and a receiver (diameter = 0.5 cm, length = 2.5 cm) and the case (2 × 10.5 × 12.5 cm) is powered by 2 AA batteries

of 2,500 mAh and carried at the hip via an elastic strap. The entire device weighs 298 g (batteries included) and has a recording capacity of over 20 h. The apparatus communicates with the PC via radio wave frequencies at RF 2.4 GHz and the transmission range of the apparatus is approximately 30 m.

The subject was equipped with the central case Nomics placed on the right hip, which was connected to two pairs of electromagnetic coils. The anteroposterior displacement

of the rib cage and abdomen and the axial displacements of the chest wall and the spine were measured using two pairs of electromagnetic coils. Each electromagnetic coil was fixed on the subject via small plastic notches, and fixed on the skin of the subject via adhesive tape (double-sided scotch tape). Thus, no sensor was in direct contact with the subject's skin. The device is made up of a circuitry of two transmitters and two receivers. Each receiver is able to receive information from both the transmitters. The first transmitter coil was placed in an anterior position at the midsternal level. The first receiver was placed in the posterior position over the spine at the midsternal level. The second receiver was placed anteriorly in the midline of the abdominal wall just above the umbilicus. Finally, the second transmitter was placed in a posterior position over the spine at the level of the umbilicus. This configuration is necessary to estimate the ventilation of the subject. The variations of the four distances measured by the electromagnetic coils are recorded at a frequency of 15.625 Hz. These four variations of distances were visualized in real-time on a PC, thanks to computer software (Chesto-soft, Nomics). All measurements of the electromagnetic coils were exported as Matlab files for processing. Based on this process, the values of ventilation were determined ($\dot{V}_{E_{\text{mag}}}$).

Data analysis

Test 1: Calibration

The data of oxygen uptake ($\dot{V}O_{2\text{IC-Cal}}$), ventilation ($\dot{V}_{E\text{IC-Cal}}$) and respiratory exchange ratio (RER_{Cal}) measured by indirect calorimetry and \dot{V}_E estimated by the electromagnetic coils ($\dot{V}_{E_{\text{mag-Cal}}}$) were averaged over the final minute of each activity (sitting, standing and walking at 4, 5, and 6 km h⁻¹). This was done so in order to establish the individual relationship of each subject, first, between $\dot{V}_{E\text{IC-Cal}}$ and EE determined by indirect calorimetry during Test 1 ($\text{EE}_{\text{IC-Cal}}$) and second, between $\dot{V}_{E_{\text{mag-Cal}}}$ and $\text{EE}_{\text{IC-Cal}}$ (Fig. 2). $\text{EE}_{\text{IC-cal}}$ was obtained by multiplying $\dot{V}O_{2\text{IC-Cal}}$ by the energy equivalent of oxygen (EEO_2). The value of EEO_2 was obtained by the table of respiratory exchange ratio (RER) proposed by Peronnet and Massicotte (1991). $\text{EE}_{\text{IC-Cal}}$ was expressed as kcal min⁻¹. For both relationships $\text{EE}_{\text{IC-Cal}} = f(\dot{V}_{E\text{IC-Cal}})$ and $\text{EE}_{\text{IC-Cal}} = f(\dot{V}_{E_{\text{mag-Cal}}})$, the equations of the linear regression and the coefficients of determination (r^2) were calculated (Table 1). Individual equations were established for each of the 11 subjects, and a group equation was established from the overall dataset (Table 1).

Test 2: Validation

The data of oxygen uptake ($\dot{V}O_{2\text{IC-Val}}$), ventilation ($\dot{V}_{E\text{IC-Val}}$) and respiratory exchange ratio (RER_{Val}) measured by indirect calorimetry and \dot{V}_E estimated by the electromagnetic coils ($\dot{V}_{E_{\text{mag-Val}}}$) were averaged over the time length (5 min) of each activity (sitting, standing and walking at 4, 5, 6 km h⁻¹). The following parameters were calculated during this period of 5 min: (1) $\text{EE}_{\text{IC-Val-REF}}$ was the reference EE obtained by the indirect calorimetry during Test 2; (2) $\text{EE}_{\text{mag-Val-INDIV}}$ was the EE obtained by two pairs of electromagnetic coils calculated by each individual relationship [$\text{EE}_{\text{IC-Cal}} = f(\dot{V}_{E_{\text{mag-Cal}}})$] determined during Test 1 and (3) $\text{EE}_{\text{mag-Val-GROUP}}$ was the EE obtained by two pairs of electromagnetic coils calculated by the group equation [$\text{EE}_{\text{IC}} = 0.2341 \times \dot{V}_{E_{\text{mag}}} - 0.5331$] determined during Test 1. To simplify the understanding of both tests, all abbreviations are mentioned in Table 2.

Statistical analysis

Test 2

A two-factor repeated measure ANOVA was performed to assess differences in the measurement of \dot{V}_E and EE by indirect calorimetry and two pairs of electromagnetic coils ($\dot{V}_{E\text{IC-Val}}$ versus $\dot{V}_{E_{\text{mag-Val}}}$, $\text{EE}_{\text{IC-Val-REF}}$ versus $\text{EE}_{\text{mag-Val-INDIV}}$ and $\text{EE}_{\text{IC-Val-REF}}$ versus $\text{EE}_{\text{mag-Val-GROUP}}$). All of the data was analyzed separately for each condition of the protocol (sitting, standing, walking at 4, 5 and 6 km h⁻¹). The coefficients of determination (r^2) were calculated to compare $\text{EE}_{\text{IC-Val-REF}}$ versus $\text{EE}_{\text{mag-Val-INDIV}}$ and $\text{EE}_{\text{IC-Val-REF}}$ versus $\text{EE}_{\text{mag-Val-GROUP}}$. The Bland and Altman method was used to assess the 95% confidence interval and the bias (mean bias) to compare ($\text{EE}_{\text{IC-Val-REF}} - \text{EE}_{\text{mag-Val-INDIV}}$) and ($\text{EE}_{\text{IC-Val-REF}} - \text{EE}_{\text{mag-Val-GROUP}}$). Results were considered statistically significant for $p < 0.05$.

Results

Test 1

The individual relationships $\text{EE}_{\text{IC-Cal}} = f(\dot{V}_{E\text{IC-Cal}})$ and $\text{EE}_{\text{IC-Cal}} = f(\dot{V}_{E_{\text{mag-Cal}}})$ are presented in Table 1. The relationship $\text{EE}_{\text{IC-Cal}} = f(\dot{V}_{E\text{IC-Cal}})$ is characterized for all subjects by coefficients of determination $r^2 = 0.99$, except for subject 11, where the coefficient is $r^2 = 0.98$. The same result is observed for the relationship

Table 1 Individual and group relationships between ventilation and energy expenditure measured with indirect calorimetry ($\dot{V}_{E_{IC-Cal}}$ and EE_{IC-Cal}) and between ventilation measured by the two pairs of

electromagnetic coils and energy expenditure measured with indirect calorimetry ($\dot{V}_{E_{mag-Cal}}$ and EE_{IC-Cal})

Subjects	$EE_{IC-Cal} = f(\dot{V}_{E_{IC-Cal}})$	r^2	$EE_{IC-Cal} = f(\dot{V}_{E_{mag-Cal}})$	r^2
1	$EE_{IC} = 0.2626 \times \dot{V}_{E_{IC}} - 0.7600$	$r^2 = 0.99$	$EE_{IC} = 0.2613 \times \dot{V}_{E_{mag}} - 0.7624$	$r^2 = 0.99$
2	$EE_{IC} = 0.2348 \times \dot{V}_{E_{IC}} - 0.8441$	$r^2 = 0.99$	$EE_{IC} = 0.2336 \times \dot{V}_{E_{mag}} - 0.7285$	$r^2 = 0.99$
3	$EE_{IC} = 0.2625 \times \dot{V}_{E_{IC}} - 0.9841$	$r^2 = 0.99$	$EE_{IC} = 0.2613 \times \dot{V}_{E_{mag}} - 0.9665$	$r^2 = 0.99$
4	$EE_{IC} = 0.2541 \times \dot{V}_{E_{IC}} - 0.6648$	$r^2 = 0.99$	$EE_{IC} = 0.2692 \times \dot{V}_{E_{mag}} - 0.8511$	$r^2 = 0.99$
5	$EE_{IC} = 0.2227 \times \dot{V}_{E_{IC}} - 0.4173$	$r^2 = 0.99$	$EE_{IC} = 0.2155 \times \dot{V}_{E_{mag}} - 0.2014$	$r^2 = 0.99$
6	$EE_{IC} = 0.2253 \times \dot{V}_{E_{IC}} - 0.3050$	$r^2 = 0.99$	$EE_{IC} = 0.2232 \times \dot{V}_{E_{mag}} - 0.1088$	$r^2 = 0.99$
7	$EE_{IC} = 0.2313 \times \dot{V}_{E_{IC}} - 0.1089$	$r^2 = 0.99$	$EE_{IC} = 0.2080 \times \dot{V}_{E_{mag}} + 0.3419$	$r^2 = 0.99$
8	$EE_{IC} = 0.2303 \times \dot{V}_{E_{IC}} - 0.2980$	$r^2 = 0.99$	$EE_{IC} = 0.2279 \times \dot{V}_{E_{mag}} - 0.3080$	$r^2 = 0.99$
9	$EE_{IC} = 0.2033 \times \dot{V}_{E_{IC}} - 0.5300$	$r^2 = 0.99$	$EE_{IC} = 0.1991 \times \dot{V}_{E_{mag}} - 0.4991$	$r^2 = 0.99$
10	$EE_{IC} = 0.2288 \times \dot{V}_{E_{IC}} - 0.2974$	$r^2 = 0.99$	$EE_{IC} = 0.2376 \times \dot{V}_{E_{mag}} - 0.4899$	$r^2 = 0.99$
11	$EE_{IC} = 0.2542 \times \dot{V}_{E_{IC}} - 1.1720$	$r^2 = 0.98$	$EE_{IC} = 0.2523 \times \dot{V}_{E_{mag}} - 1.1792$	$r^2 = 0.98$
Group	$EE_{IC} = 0.2318 \times \dot{V}_{E_{IC}} - 0.4679$	$r^2 = 0.97$	$EE_{IC} = 0.2341 \times \dot{V}_{E_{mag}} - 0.5331$	$r^2 = 0.97$

Physical activity realized by each subject: sitting at rest, standing at rest and walking at 4, 5 and 6 km h⁻¹. Thus, five points have been used to establish the individual relationship between ventilation and energy expenditure. Fifty-five (11 subject × 5 points) points have been used to establish the group relationship between ventilation and energy expenditure
 r^2 = coefficient of determination

Table 2 The whole of data measured or estimated during the tests 1 and 2

	Test 1—calibration (Cal)				Test 2—validation (Val)			
Parameters measured by indirect calorimetry (IC)	$\dot{V}_{O_{2IC-Cal}}$	$\dot{V}_{E_{IC-Cal}}$	RER_{Cal}	EE_{IC-Cal}	$\dot{V}_{O_{2IC-Val}}$	$\dot{V}_{E_{IC-Val}}$	RER_{Val}	$EE_{IC-Val-REF}$
Parameters estimated by the electromagnetic coils (mag)	—	$\dot{V}_{E_{mag-Cal}}$	—	—	—	$\dot{V}_{E_{mag-Val}}$	—	$EE_{mag-Val-INDIV}$ $EE_{mag-Val-GROUP}$

Cal calibration, Val validation, IC indirect calorimetry, mag electromagnetic coils, \dot{V}_{O_2} oxygen consumption, \dot{V}_E ventilation, RER respiratory exchange ratio, EE energy expenditure, REF reference, $INDIV$ individual equations, $GROUP$ group equation

$EE_{IC-Cal} = f(\dot{V}_{E_{mag-Cal}})$. The two group equations are characterized by coefficients of determination $r^2 = 0.97$.

Test 2

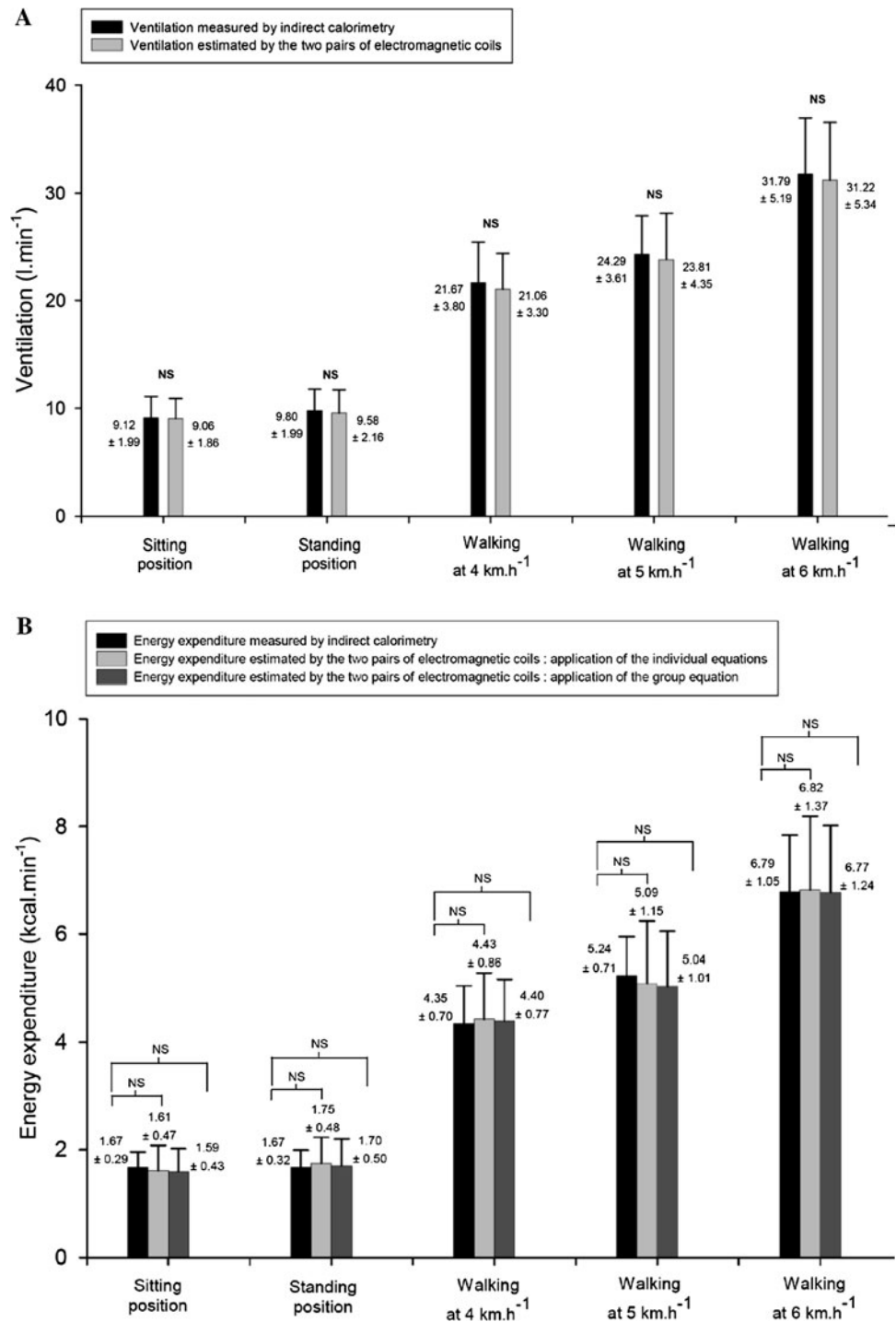
Figure 3a shows the mean \dot{V}_E values measured by indirect calorimetry ($\dot{V}_{E_{IC-Val\ mean}}$) and estimated by two pairs of electromagnetic coils ($\dot{V}_{E_{mag-Val\ mean}}$) for all the subjects in each of the different activities. The two-factor repeated measures ANOVA showed that there is no significant difference between $\dot{V}_{E_{IC-Val\ mean}}$ and $\dot{V}_{E_{mag-Val\ mean}}$ for each activity, and that these parameters gradually increase with exercise intensity ($p < 0.001$).

Figure 3b shows the mean EE values measured by indirect calorimetry ($EE_{IC-Val-REF\ mean}$) and estimated by the two pairs of electromagnetic coils through the application of the individual equations ($EE_{mag-Val-INDIV\ mean}$) or

the application of the group equation ($EE_{mag-Val-GROUP\ mean}$), for all the subjects during the different activities. The two-factor repeated measures ANOVA showed that there is no significant difference between $EE_{IC-Val-REF\ mean}$ and $EE_{mag-Val-INDIV\ mean}$ for each activity. It also shows that EE ($EE_{IC-Val-INDIV}$ and $EE_{mag-Val-INDIV}$) gradually increases in proportion to the intensity of the exercise ($p < 0.001$). The same two results are reported between $EE_{IC-Val-REF\ mean}$ and $EE_{mag-Val-GROUP\ mean}$.

The mean differences (%) were calculated between $EE_{IC-Val-REF}$ and $EE_{mag-Val-INDIV}$ and between $EE_{IC-Val-REF}$ and $EE_{mag-Val-GROUP}$. The comparison shows that the mean differences are smaller between $EE_{IC-Val-REF}$ and $EE_{mag-Val-GROUP}$ for the sitting activity at rest and the walking activities at 4, 5 and 6 km h⁻¹. For the standing activity at rest, the difference is lower between $EE_{IC-Val-REF}$ and $EE_{mag-Val-INDIV}$. The global percentage is presented in Table 3.

Fig. 3 a Ventilation measured by indirect calorimetry ($\dot{V}_{E_{IC-Val\ mean}}$) and estimated by the two pairs of electromagnetic coils ($\dot{V}_{E_{mag-Val\ mean}}$) during the five different activities, for the whole of the group. **b** Energy expenditure measured by indirect calorimetry ($EE_{IC-Val-REF\ mean}$) and estimated by the two pairs of electromagnetic coils with the application of the individual ($EE_{mag-Val-INDIV\ mean}$) and the group ($EE_{mag-val-GROUP\ mean}$) equations during the five different activities. *NS* no significant difference



The mean bias between $EE_{IC-Val-REF}$ and $EE_{mag-Val-INDIV}$ and between $EE_{IC-Val-REF}$ and $EE_{mag-Val-GROUP}$ were calculated from the sitting, standing and walking exercise data. The mean bias values are presented in Table 3.

Figure 4 shows the individual differences in \dot{V}_E and EE between the electromagnetic coils and indirect calorimetry for the sitting and standing activities at rest and the walking exercises at 4, 5 and 6 km h⁻¹. Individual differences

($\dot{V}_{E_{mag-Val}} - \dot{V}_{E_{IC-Val}}$) in \dot{V}_E ranged between +2.5 and -2.3 l min⁻¹ for the resting activities (sitting and standing) and between +7.0 and -5.3 l min⁻¹ for the walking activities (4, 5 and 6 km h⁻¹) (Fig. 4a). Individual differences ($EE_{mag-Val-INDIV} - EE_{IC-Val-INDIV}$) in EE, calculated with the individual equations, ranged between +0.74 and -0.63 kcal min⁻¹ for the at rest activities (sitting and standing) and between +1.70 and -1.35 kcal min⁻¹ for

Table 3 Mean values of energy expenditure ($EE_{IC-Val-REF}$, $EE_{mag-Val-INDIV}$, $EE_{mag-Val-GROUP}$), mean differences and mean bias between the reference measurement and the two estimate values of energy expenditure for the five different activities

Variables	Mean value ($\pm SD$) ($EE_{IC-Val-REF}$)	Mean value ($\pm SD$) ($EE_{mag-Val-INDIV}$)	Mean value ($\pm SD$) ($EE_{mag-Val-GROUP}$)	Mean difference (%) $EE_{IC-Val-REF}$ VERSUS $EE_{mag-Val-INDIV}$	Mean difference (%) $EE_{IC-Val-REF}$ VERSUS $EE_{mag-Val-GROUP}$	Mean Bias ($\pm SD$) ($EE_{IC-Val-REF}$ - $EE_{mag-Val-INDIV}$)	Mean Bias ($\pm SD$) ($EE_{IC-Val-REF}$ - $EE_{mag-Val-GROUP}$)
Sitting at rest EE (kcal min ⁻¹)	1.67 (± 0.29)	1.61 (± 0.47)	1.59 (± 0.43)	19.0% (± 13.5)	17.0% (± 13.1)	0.057 (± 0.396)	0.083 (± 0.348)
Standing at rest EE (kcal min ⁻¹)	1.67 (± 0.32)	1.75 (± 0.48)	1.71 (± 0.50)	14.1% (± 17.1)	19.3% (± 16.8)	-0.079 (± 0.321)	-0.03 (± 0.385)
Walking 4 km h ⁻¹ EE (kcal min ⁻¹)	4.35 (± 0.70)	4.43 (± 0.86)	4.40 (± 0.77)	13.3% (± 8.1)	10.8% (± 9.0)	-0.083 (± 0.705)	-0.043 (± 0.647)
Walking 5 km h ⁻¹ EE (kcal min ⁻¹)	5.24 (± 0.71)	5.09 (± 1.15)	5.04 (± 1.01)	17.6% (± 6.3)	14.7% (± 8.4)	0.149 (± 1.032)	0.204 (± 0.942)
Walking 6 km h ⁻¹ EE (kcal min ⁻¹)	6.79 (± 1.05)	6.82 (± 1.37)	6.77 (± 1.25)	11.7% (± 6.9)	9.3% (± 6.1)	-0.027 (± 0.952)	0.02 (± 0.801)

For example: $EE_{IC-Val-REF}$ VERSUS $EE_{mag-Val-INDIV}$

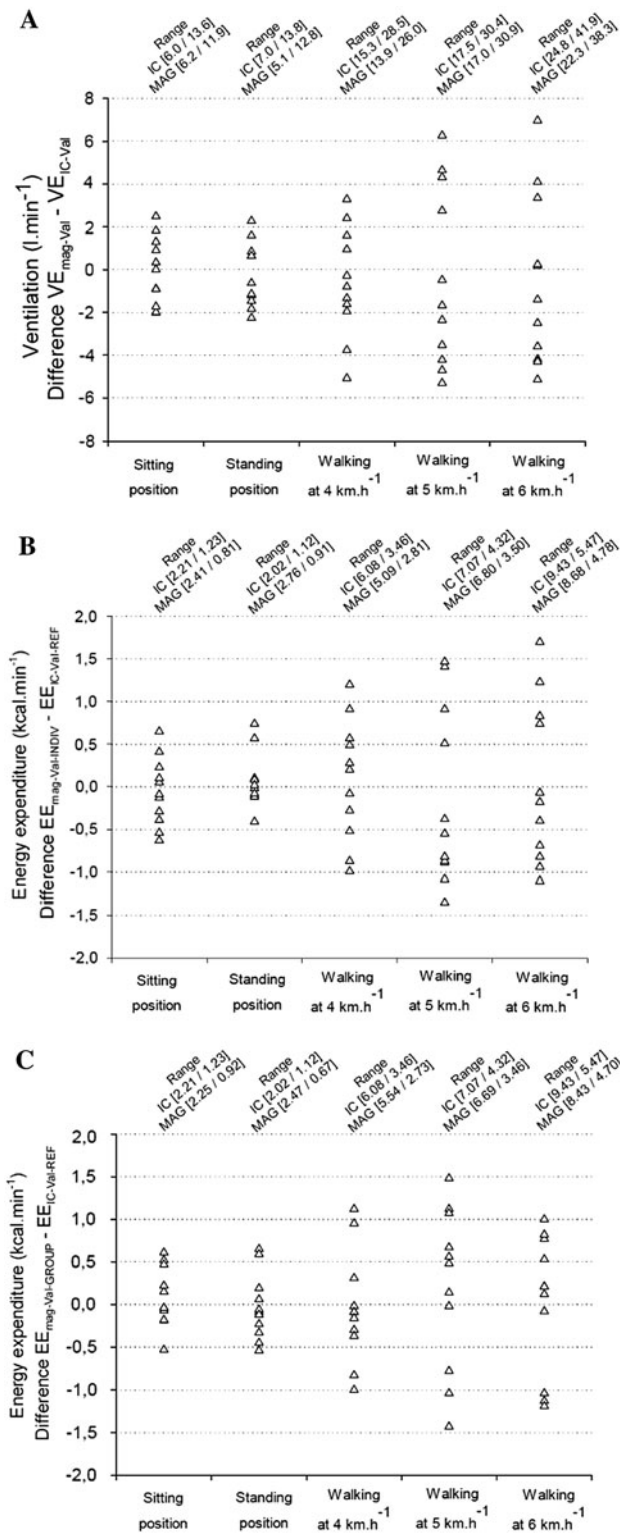
Mean difference (%) = Difference between $EE_{IC-Val-REF}$ and $EE_{mag-Val-INDIV}$ = $(1 - [EE_{mag-Val-INDIV}/EE_{IC-Val-REF}]) \times 100$

the structured walking activities (4, 5 and 6 km h⁻¹) (Fig. 4b). Individual differences ($EE_{mag-Val-GROUP} - EE_{IC-Val-GROUP}$) in EE, calculated with the group equation, ranged between +0.60 and -0.54 kcal min⁻¹ for the at rest activities (sitting and standing) and between +1.48 and -1.43 kcal min⁻¹ for the structured walking activities (4, 5 and 6 km h⁻¹) (Fig. 4c).

With regard to the pooled data (sitting and standing at rest and walking exercise) $EE_{IC-Val-REF}$ was significantly correlated with $EE_{mag-Val-INDIV}$ ($EE_{IC-Val-REF} = 0.351 + 0.912 \times EE_{mag-Val-INDIV}$, $r^2 = 0.90$, $p < 0.001$) and $EE_{IC-Val-REF}$ was significantly correlated with $EE_{mag-Val-GROUP}$ ($EE_{IC-Val-REF} = 0.295 + 0.936 \times EE_{mag-Val-GROUP}$, $r^2 = 0.91$, $p < 0.001$).

Discussion

The purpose of this study was to validate a new method of estimating EE, under rest and during moderate exercise conditions, in relation to the non-invasive estimation of \dot{V}_E , and to show the feasibility of our method to estimate EE from applying a group equation in comparison with the individual equations. This study, which was conducted exclusively under controlled laboratory conditions, is the first of its kind to have tested a system based on two pairs of electromagnetic coils with the objective of estimating EE. The first part of our study set out to establish the individual and the group relationship between EE (measured from a system of indirect calorimetry) and \dot{V}_E of the subject (measured by indirect calorimetry and estimated by the two pairs of electromagnetic coils). Then, we obtained two types of relationship: the relationship $EE_{IC-Cal} = f(\dot{V}_{E_{IC-Cal}})$ and the relationship $EE_{IC-Cal} = f(\dot{V}_{E_{mag-Cal}})$ (Test 1). The latter relationship was used in Test 2 to determine EE from the two pairs of electromagnetic coils with the application of the individual equations or the group equation. The following activities were carried out during Test 2: sitting at rest, standing at rest, walking at 4, 5 and 6 km h⁻¹. Each activity was performed during a period of 5 min. The results show no significant difference between the values of $EE_{IC-Val-REF}$ and $EE_{mag-Val-INDIV}$ and between the values of $EE_{IC-Val-REF}$ and $EE_{mag-Val-GROUP}$. This is the overall result which was found for all activities carried out in Test 2. These accurate results, found in sitting and standing conditions at rest, and during walking exercises at 4, 5 and 6 km h⁻¹, seem to validate this method based on our new device which aims at estimating EE under different conditions. This study also shows the advantage of using a group equation to estimate EE. It must also be mentioned that this device presents very few constraints, and is very user friendly due to its small weight and size and its capacity for transmitting radio wave



◀ **Fig. 4 a** Individual differences ($\dot{V}_{E_{mag-val}} - \dot{V}_{E_{IC-val}}$) in ventilation ($l \cdot min^{-1}$) between the electromagnetic coils (MAG) and the indirect calorimetry system (IC) for each activity. **b** and **c** Individual differences ($EE_{mag-val-INDIV} - EE_{IC-val-REF}$ and $EE_{mag-val-GROUP} - EE_{IC-val-REF}$) in energy expenditure ($kcal \cdot min^{-1}$) between the electromagnetic coils (MAG) and the indirect calorimetry system (IC) for each activity. Application of the individual equations (**b**) to estimate $EE_{mag-val-INDIV}$ and of the group equation (**c**) to estimate $EE_{mag-val-GROUP}$. For the graphs **a**, **b** and **c**, the range of ventilation and energy expenditure estimate by the electromagnetic coils (MAG) and measured with the indirect calorimetry system (IC) is mentioned at the top of the graphs [maxi/mini]

values commonly found in related literature (Dwyer et al. 2009; Saltin and Astrand 1967; St-Onge et al. 2007; Wasserman et al. 1986) and are not significantly different from values measured by the reference system of indirect calorimetry (Fig. 3a). Furthermore, Fig. 4a presents slight differences between \dot{V}_E estimated by the electromagnetic coils and measured by the indirect calorimetry system. This difference is less than $\pm 2.5 l \cdot min^{-1}$ during activities at rest (sitting and standing). It is slightly higher for walking activities ($\pm 7.0 l \cdot min^{-1}$) and this result is explained due to the greater range of \dot{V}_E during walking exercises. However, other non-invasive and portable devices, based on the respiratory inductive plethysmography (RIP), lead to the estimation of \dot{V}_E in a relatively precise way (Ancoli-Israel et al. 1985; Fiamma et al. 2007; Heldt 1988; Leino et al. 2001; Neumann et al. 1998; Stick et al. 1992). Nevertheless, the RIP technique is based on the evaluation of the movements of the rib cage and the abdomen from a two-degrees-of-freedom model (Konno and Mead 1967). Thus, this technique allows for the evaluation of \dot{V}_E through clinical examinations and the monitoring of the vital parameters under controlled conditions. Finally, the apparatuses based on the RIP technique make it impossible to estimate EE from the estimation of \dot{V}_E . Thus, the innovative concept of our new device lies within this application.

The fat mass values of the subjects range between 20.3 and 8.6%. These percentages of fat mass are within the normal ranges for healthy male subjects aged 22 to 37 years (Jackson et al. 2002). The subjects present low percentages of fat mass yet three of subjects were slightly overweight (WHO 1995). Thus, the soft tissues present at abdomen level are low and do not affect the estimation of \dot{V}_E starting from the two pairs of electromagnetic coils. The same observation can be made on other subjects of the study. Thus, the correct results obtained from the two pairs of electromagnetic coils to estimate EE are probably explained by the small percentages of fat mass and the absence of important soft tissues at abdomen level. We could be lead to thinking that the estimation of EE from the two pairs of electromagnetic coils could be more challenging in patients with more consequential fat mass. In fact, displacements of the soft tissues at abdomen level can

measurements (30 m). Henceforth, it would be possible to estimate daily EE even in a house or an apartment.

Values of \dot{V}_E estimated from the two pairs of electromagnetic coils during sitting and standing positions and during walking at 4, 5 and 6 km h⁻¹ correspond to the

involve variations in the abdominal distances without being even slightly related to breathing. These displacements are even more accentuated during walking exercises. Indeed, the movement of the hips carried out during walking involves oscillations of the soft tissues. It will be necessary to take into account these oscillations so as to make it possible to estimate the ventilation of the overweight subjects. Hence, in relation to the fat mass data and the number of subjects, a limitation to the study could be the size and homogeneity of the recruited sample.

The most interesting result of this study is that there is no significant difference in EE between the values obtained from the two pairs of electromagnetic coils (application of the individual and group equations), and the reference system of indirect calorimetry. This result is found for all the activities: sitting and standing at rest, walking at 4, 5 and 6 km h⁻¹ (Fig. 3b). However, the mean value of EE in a sitting position at rest seems slightly overestimated compared to the value obtained from the Harris and Benedict equation ($EE_{IC-REF-mean} = 1.67 \pm 0.29 \text{ kcal min}^{-1}$ vs. $EE_{Harris \& Benedict} = 1.24 \pm 0.11 \text{ kcal min}^{-1}$) (Harris and Benedict 1919). Nevertheless, it may be observed that the values of resting EE obtained by the electromagnetic coils are very close to the values obtained by indirect calorimetry : $EE_{sitting-mag-INDIV} = 1.61 (\pm 0.47)$ and $EE_{sitting-mag-GROUP} = 1.59 (\pm 0.43)$ versus $EE_{sitting-IC-REF} = 1.67 (\pm 0.29)$; $EE_{standing-mag-INDIV} = 1.75 (\pm 0.48)$ and $EE_{standing-mag-GROUP} = 1.71 (\pm 0.50)$ versus $EE_{standing-IC-REF} = 1.67 (\pm 0.32)$ (Table 3). These closely related values (with the application of the individual and the group equations) seem to attest to the validity of the electromagnetic coils to estimate resting EE compared to the reference method. This result is confirmed by the low bias calculated in Table 3. The low bias demonstrates the proximity of the values between our portable device and the reference method. Furthermore, Fig. 4b, c presents slight differences between EE estimated by the electromagnetic coils and measured by the indirect calorimetry system. This difference is less than $\pm 0.74 \text{ kcal min}^{-1}$ (individual equations) and $\pm 0.60 \text{ kcal min}^{-1}$ (group equation) during activities at rest (sitting and standing). It is slightly higher for walking activities ($\pm 1.70 \text{ kcal min}^{-1}$, individual equations; $\pm 1.48 \text{ kcal min}^{-1}$, group equation) and this result is justified due to the greater range of EE during walking exercises. Finally, there is a strong correlation ($r^2 = 0.90$, $p < 0.001$) between the parameters of $EE_{IC-Val-REF}$ and $EE_{mag-Val-INDIV}$ for all data of EE. A strong correlation ($r^2 = 0.91$, $p < 0.001$) is also calculated between the parameters of $EE_{IC-Val-REF}$ and $EE_{mag-Val-GROUP}$ for all data of EE. From the overall results of this study, it seems that the EE calculated from the application of the group equation achieves better results compared to EE resulting from the application of

individual equations. The mean difference between $EE_{IC-Val-REF}$ and $EE_{mag-Val-GROUP}$ is lower in sitting position at rest and during walking at 4, 5 and 6 km h⁻¹ compared to the mean difference between $EE_{IC-Val-REF}$ and $EE_{mag-Val-INDIV}$ (Table 3). These results support the validation of our new method to estimate EE under resting conditions (sitting and standing) and during walking at 4, 5 and 6 km h⁻¹. Indeed, our work presents similar results to other studies having studied heart rate parameters or having explored the SensorWear Armband[®] (SWA) actimeter for example. Kurpad et al. present a coefficient of correlation of $r = 0.90$, for the relationship $\dot{V}O_2 = f(\text{HR})$ in an adult population during a period of 24 h. The heart rate monitor was compared with an indirect calorimetric system (Kurpad et al. 2006). The SWA was also compared to the method of indirect calorimetry. This actimeter presents coefficients of correlation of $r = 0.77$ and $r = 0.84$ in patients with type 2 diabetes and cancer patients, respectively (Cereda et al. 2007; St-Onge et al. 2007). Finally, two other studies show similar results with our prototype, in comparison to the technique of indirect calorimetry. The Actiheart[®] actimeter presents a coefficient of determination $r^2 = 0.84$, for an adult population in resting conditions and during walking exercise on a treadmill (Brage et al. 2005). The second study presents a coefficient of determination $r^2 = 0.91$, for a population of 12-year-old children in resting conditions and during walking and running exercises on a treadmill (Corder et al. 2007b). These results show that our prototype is also as accurate as some already existing methods (heart rate monitor, SensorWear Armband[®], Actiheart[®]) which are employed to estimate EE under different conditions.

We are well aware that our study only covers the activities of light to moderate intensities, with \dot{V}_E levels lower than 50 l min⁻¹. This range of exercise corresponds to the linear part of the relationship between \dot{V}_E and EE. Future research should be conducted so as to validate this new device with regard to vigorous activity ($>50\% \dot{V}O_{2max}$). Furthermore, the activities explored in this study are restricted to at rest conditions (sitting and standing) and light structured activities such as walking exercises at 4, 5 and 6 km h⁻¹. For future research, it will be necessary to test our device on other activities such as: climbing stairs, cycling a bicycle, running at different speeds, playing basketball or jumping on a trampoline as previously explored by Arvidsson et al. (2007) and (2009). Finally, improvements could still be made so as to optimize this method of estimation of EE.

The calibration protocol of the two pairs of electromagnetic coils requires many experimental trials in order to estimate \dot{V}_E . First of all, it is necessary to measure \dot{V}_E and the variations of distances of the rib cage and the abdomen with a spirometer and the two pairs of electromagnetic

coils, respectively. This experiment is used to develop multi-linear regressions so as to estimate \dot{V}_E from the variations of the distances measured by the two pairs of electromagnetic coils. A multi-linear regression is necessary for each activity performed by the subject (sitting, standing, walking at 4, 5 and 6 km h⁻¹). Moreover, these mathematical equations must be developed for each subject using this new device. It would be necessary to simplify this calibration protocol by automating the process. The subject would then have to install the system and perform several sets of breathing in order to calibrate the device.

We are well aware that the calibration of our prototype has been developed within one population type, and that the validation of this prototype, using the multi-linear regression which was developed, has used the same sample of subjects. The group equation seems to be more efficient than the individual equations, and demonstrates the feasibility of our method to estimate EE with the two pairs of electromagnetic coils. This group equation will have to be tested on other subjects during future studies.

Furthermore, once the automation of the device has been achieved, it would be necessary to integrate this system into clothing shirt or vest so as to make it possible to process measurements under daily life circumstances. The data would be recorded directly onto an integrated hard disk, to make it possible to follow-up subjects over a period of 24 h. These future studies should enable us to test the reproducible capacity of this EE assessment method. Studies have also begun so as to develop clothing which may measure physiological parameters, but which is not yet capable of estimating EE (LifeShirtTM, Vivometrics; SmartshirtTM, Sensatex) (Grossman 2004; Park and Jayaraman 2005). In order to integrate our prototype into clothing, it would beforehand have to be tested on overweight or obese subjects so as to evaluate the ability of this method in the estimation of EE. The development of specific algorithms would be necessary to take into account the soft tissues present at abdomen level.

Conclusion

In conclusion, according to the mean values of \dot{V}_E and EE—the mean bias, the 95% confidence interval and the coefficients of determination, our method which is based on the two pairs of electromagnetic coils provided similar individual estimates of \dot{V}_E and EE compared with the indirect calorimetric system. This system provided an accurate estimation of \dot{V}_E and EE during different body postures (sitting and standing at rest) and ambulatory activities (walking at 4, 5 and 6 km h⁻¹). Hence, this new device shows promise in being a valid tool in the

estimation of EE over a wide range of activities of light to moderate intensity.

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