Global Journal of Obesity, Diabetes and Metabolic Syndrome

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Dates: Received: 30 October, 2014; **Accepted:** 25 March, 2015; **Published:** 29 March, 2015

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www.peertechz.com

ISSN: 2455-8583

Keywords: Indirect calorimetry; Metabolism tracker; Energy expenditure; Respiratory quotient

Research Article

Personalized Indirect Calorimeter for Energy Expenditure (EE) Measurement

Abstract

Background and aims: A personal indirect calorimeter allows everyone to assess resting and non-resting energy expenditure, thus enabling accurate determination of a person's total calorie need for weight management and fitness. The aim of this study is to compare the performance of a new personal metabolic rate tracker based on indirect calorimetry, Breezing®, with the Douglas bag method, the gold standard method for energy expenditure (EE) measurement.

Methods: Energy expenditures (EE) at rest and during activities, and respiratory quotient (RQ) were measured for 12 healthy subjects, including 7 male and 5 female under different living conditions. A total of 314 measurements were performed with Breezing®, and the results were compared with those by the Douglas bag method.

Results: R-squared correlation coefficients (R^2) between the data obtained with Breezing® and the Douglas bag method were 0.9976, 0.9986, 0.9981, and 0.9980, for VO_2, VCO_2, EE, and RQ respectively.

Conclusions: The EE and RQ values determined by Breezing® are in good agreement with those by the Douglas bag method.

Introduction

A person's resting energy expenditure (REE) is his/her energy expenditure under resting conditions, which is the minimal need of energy to sustain life. During physical activities, the energy expenditure (EE) will be higher, depending on the type, intensity and duration of each physical activity. Indirect calorimetry is the most well established approach for accurate assessment of REE and EE, and widely used in clinical and fitness labs for nutritional support, exercise recommendation, and weight management [1,2]. However, traditional indirect calorimetry equipment is bulky, expensive, and complicated to calibrate and use. For this reason, equations have been created to estimate REE. Because REE depends on age, gender, genes and other attributes of the person, which thus varies widely from person to person, the estimated REE using the well known Harris-Benedict equation [3] or improved equations[4] can be significantly different from the person's true REE value. Additionally, a person's REE may vary over time. For example, exercise may increase REE, and reduction of calorie intake may decrease REE [5,6]. To fulfill the needs, a mobile indirect calorimeter, Breezing® was developed to facilitate personalized REE measurement and tracking. This pocket-sized indirect calorimeter measures oxygen consumption rate (VO_2) and carbon dioxide production rate (VCO_2) in breath with a colorimetric technology, from which REE and EE are determined according to the well-known Weir equation [7]. It also measures respiratory quotient ($RQ = VCO_2/VO_2$), which is indicative of the source of energy used at the time of the measurement (e.g., carbohydrate vs. fat).

In order to evaluate the accuracy and performance of the mobile indirect calorimeter, a comparative study was carried out using mobile indirect calorimeter and the gold standard Douglas bag method. Over 300 measurements with human objects were performed following the instructions of the mobile indirect calorimeter and standard protocols of the Douglas Bag method. Statistical analysis methods, such as linear regression and Bland-Altman plot were used to establish quantitative correlation between of the values from the mobile indirect calorimeterand that from the gold standard method.

Materials and Methods

Subjects

Twelve healthy adults from Arizona State University (ASU), including 7 male and 5 female, were tested during this study. Their ages ranged from 21 to 38 years and their body mass indices (BMI) ranged from 16.9 to 32.2kg/m² (Table 1 and Table 2). The study was approved by the Institutional Review Board of Arizona State University (IRB protocol #1012005855) and all subjects participated in the study voluntarily, providing written informed consent prior to participation. The study was carried out at ASU from January 2013 to June 2014.

The mobile indirect calorimeter, Breezing® Device

The Breezing® device uses a sensor cartridge and a flow meter to determine the rate of consumed oxygen and produced carbon dioxide in the breath. The sensing technology of the new indirect calorimeter, which used a cell-phone camera as the optical detector, was previously reported [8]. The current Breezing® device uses a QR code to carry calibration parameters of a single-use sensor cartridge, which can be scanned and recognized by the mobile application (app). The device is 6.0 oz. (170 g), and 1.8 in × 2.1 in × 4.8 in (4.7 cm × 5.4 cm × 12.3 cm), and connects wirelessly to an iOS mobile device, using Bluetooth 4.0 technology.

The mobile device (phone or tablet) receives data from the device, processes information, and then provides test results and summaries through a graphic user interface. It determines the energy expenditure from the measurement of VO_2 and VCO_2 according to the Weir equation, along with RQ. In addition to the sensor cartridge, the Breezing® device is used with a non-rebreathing 2-valvesmouthpiece, as shown in Figure 1.

Methods

Before the study, the participants were familiarized with the device, the app, and the testing procedure. The energy expenditures of the subjects were tested under different conditions, including while resting, after physical activity (walking, jogging, running, or exercise in the gym), after eating, and after office work in order to cover a wide energy expenditure range (1000 -4000 kcal/day).

In order to make a real time comparison between the Breezing® device and the Douglas bag method, the gas outlet of the Breezing® device was directly connected to a Douglas bag setup to allow the same breath sample to be simultaneously measured by Breezing® device and by the Douglas bag method (see below).

Breezing® device has a pre-calibrated built-in flow sensor, which can accurately measure the breath flow rate in a range of 0 to 20 L/min with an accuracy within 3%. The single-use sensor cartridge is packed in sealed Mylar Bags with a lifetime over a year at room temperature.

The O_2 and CO_2 concentrations of the breath sample collected in the Douglas bag were measured using reference methods. A commercial electrochemical sensor (VTI Oxygen Analyzer, Vascular Technology, Nashua, NH 03062) was used for O_2 detection and a commercial infrared sensor (Telaire 7001, GE, Goleta, CA) modified with a Nafion drying tube was used for CO_2 detection. Similar to the Breezing® device, EE was calculated according to Weir Equation and RQ was obtained from the ratio of produced carbon dioxide/consumed oxygen.

During the test, subjects breathed through a disposable mouthpiece connected to the Breezing® device for about 1-2 minutes, depending on the exhalation rate of the user, and until a total of 6 liters of exhaled air was collected. The exhalation volumes were corrected for standard dry temperature, and pressure conditions. The average oxygen and carbon dioxide concentrations from the breaths were measured. While the Breezing® device assessed exhalation rates via the use of an integrated flow meter, the Douglas Bag method assessed the exhalation rate by measurement of total time to reach 6L exhalation volume. The oxygen consumption rate and carbon dioxide production rate assessed by Breezing® device and Douglas Bag Method were then compared.

Energy expenditure assessment protocol

REE measurements were taken at resting state, including any of the following conditions: 1) immediately upon waking with overnight (8-hour) fasting; 2) afterat least 4 hours from a meal (~500 kcal); 3) after at least 4 hours from moderate exercise; 4) after at least 12 hours from strenuous exercise. To measure energy expenditure other than REE, the subjects were tested right after exercises or eating, such as doing the measurement as soon as the running is finished.

Data and Statistical analysis

All data were reported as mean ± SD. The four parameters (VO_2, VCO_2, EE and RQ) were compared by linear regression and evaluated Bland-Altman plots (Figure 2). Statistical analysis of the data was performed using Origin Pro 8 (Origin Lab Corporation).

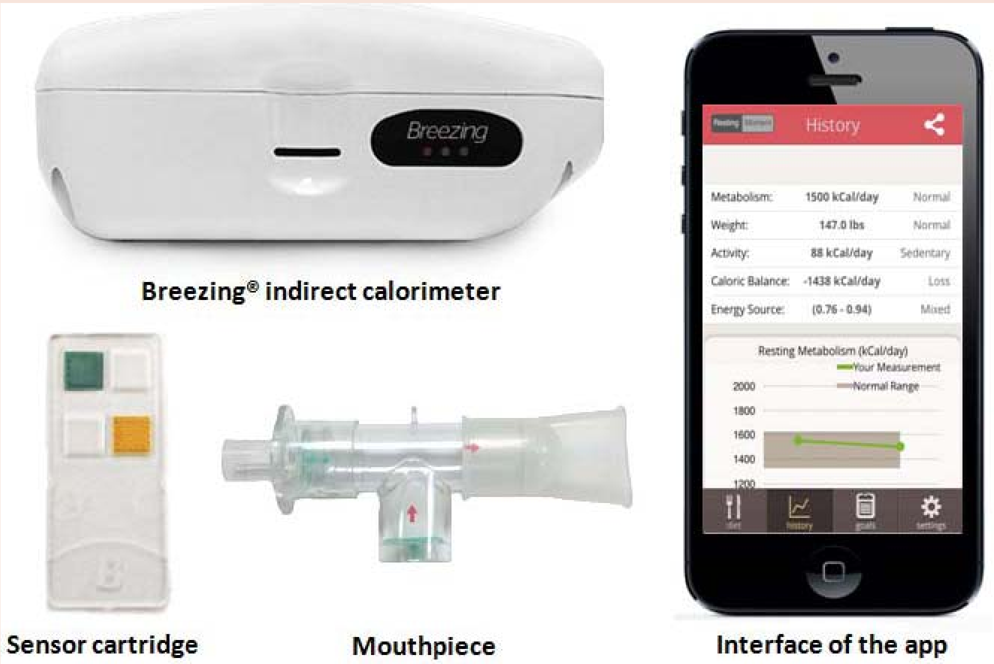

Figure 1: The Breezing® indirect calorimeter, sensor cartridge, mouthpiece, and iPhone interface of the application.

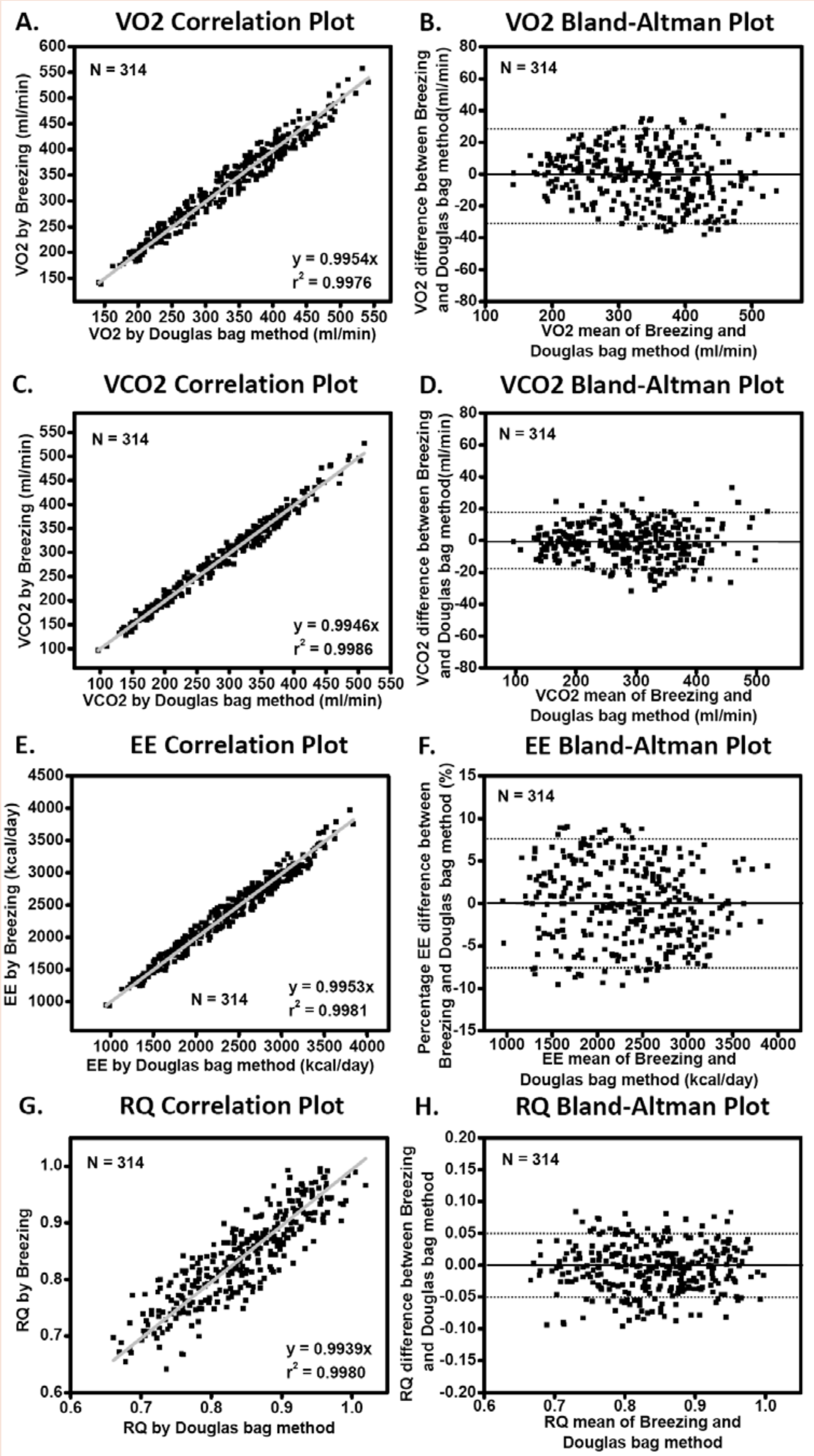

Figure 2: Comparison between the Breezing® device and Douglas bag method. (A) VO_2 correlation plot; (B) VO_2 Bland-Altman plot; (C) VCO_2 correlation plot; (D) VCO_2 Bland- Altman plot; (E) EE correlation plot; (F) EE Bland-Altman plot (in percentage); (G) RQ correlation plot; (H) RQ Bland-Altman plot.

Results

Over three hundred tests were performed and the comparison between the Breezing® device and the Douglas bag method was made to evaluate the correlation between these two methods. The results are shown in Figure 2, and summarized as follows:

VO_2 measurements

Measured oxygen consumption rates (VO_2) were in the range of 150 to 550 mL/min. Linear fitting comparing the Breezing®'s oxygen consumption rates and the corresponding Douglas bag values had a slope of 0.9954anda R-squared correlation coefficient (R^2) of 0.9976 (Figure 2A). The mean difference of the measured VO_2 between the Breezing® device and Douglas bag method is -0.6 mL/min, indicating there is no significant difference between these two methods. For each individual VO_2 test, the difference between two methods was within ±28 mL/min (Figure 2B).

VCO_2 measurements

Measured carbon dioxide production rates (VCO_2) were in the range of 100 to 500 mL/min. Linear fitting comparing Breezing®'s

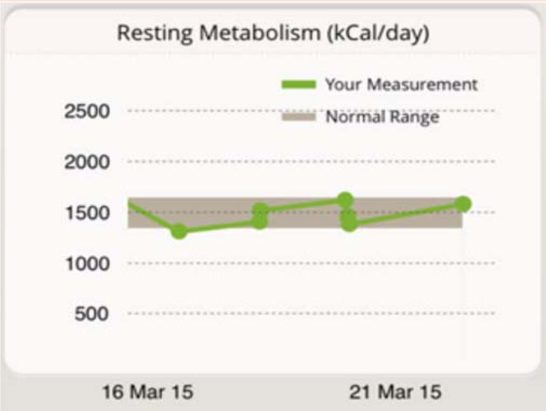

Figure 3: Example of REE monitoring for a study subject at different times, using Breezing® indirect calorimeter at different days.

Table 1: Personal information of subjects enrolled in the study.

Subject Index	Age	Gender	Weight (kg)	Height (cm)	BMI
Subject-1	28	M	82.7	167.6	29.4
Subject-2	27	F	49.9	161.3	19.2
Subject-3	23	F	65.0	162.6	24.6
Subject-4	21	M	70.0	181.6	21.2
Subject-5	24	M	90.5	167.6	32.2
Subject-6	23	M	70.0	180.3	21.5
Subject-7	38	F	64.9	161.3	24.9
Subject-8	26	F	47.6	167.6	16.9
Subject-9	25	M	65.3	175.3	21.3
Subject-10	33	M	60.9	175.3	19.8
Subject-11	30	F	52.2	160.0	20.4
Subject-12	26	M	63.5	175.3	20.7

Table 2: Summary of participating subjects.*

	N	Age (yr)	Height (cm)	Weight (kg)	BMI (kg/m²)
Men	7	25.7 ± 3.9 (21-33)	174.7 ± 5.5 (167.6-181.6)	71.9 ± 10.9 (60.9-90.5)	23.7 ± 4.9 (19.8-32.2)
Women	5	28.8 ± 5.7 (23-38)	162.6 ± 3.0 (160.0-167.6)	55.9 ± 8.4 (47.6-65.0)	21.2 ± 3.5 (16.9-24.9)
Total	12	27.0 ± 4.8 (21-38)	169.7 ± 7.7 (160.0-181.6)	65.2 ± 12.5 (47.6-90.5)	22.7 ± 4.4 (16.9-32.2)

*Parameters including: mean±standard deviation, and minimum and maximum values.

carbon dioxide production rates and the corresponding Douglas bag values had a slope of 0.9946, and a R^2 of 0.9986 (Figure 2C). The mean difference of the measured VCO_2 between the Breezing® device and Douglas bag method is 1.4 mL/min, indicating there is no significant difference between these two methods. For individual VCO_2 test, the difference between two methods is within ±19 mL/min (Figure 2D).

EE measurements

Measured energy expenditure (EE) ranged from 1000 to 4000 kcal/day. Linear fitting comparing Breezing®'s EE values and the corresponding Douglas bag values had a slope of 0.9953 and an R^2 of 0.9981 (Figure 2E). The mean difference of the measured EE between the Breezing® device and Douglas bag method is 5.7 kcal/day, indicating there is no significant difference between these two methods. For individual EE test, the difference between two methods is within ±7.6% (Figure 2F).

RQ measurements

Measured respiratory quotient (RQ) ranged from 0.65 to 1.00. Linear fitting comparing Breezing®'s RQ values and the corresponding Douglas bag values had a slope of 0.9939 and an R^2 of 0.9980 (Figure 2G). The mean difference of the measured RQ between the Breezing® device and Douglas bag method is 0.004, indicating there is no significant difference between these two methods. For individual RQ test, the difference between two methods is within ±0.05 (Figure 2H).

Discussion

EE is an important parameter provided by Breezing® device. According to the test results from Figure 2F, the difference was within 10% for the range of 1000 to 4000 kcal/day. Since EE is determined by the Weir equation [7],

$$EE= [3.9 (VO_2) + 1.1 (VCO_2)] \times 1.44 \quad (1)$$

Where EE is in kcal/day and VO_2 and VCO_2 are in mL/min, the accuracy of EE measurement is determined by the VO_2 and VCO_2 measurements. The Bland-Altmanplots for both VO_2 and VCO_2 showed that the absolute differences between Breezing® device and Douglas bag were less than 40 mL/min and this difference was even smaller at the lower end of the analyzed range. In contrast to previous metabolic rate measurement products that use electrochemical [9] or fluorimetric [10] sensors to determine breath oxygen concentration, assuming a carbon dioxide production rate with RQ = 0.85, Breezing® device measures both the breath oxygen and carbon dioxide concentrations to provide accurate measurement of EE, without an assumption that RQ is fixed. Since RQ is a reflection of the substrate of the energy used [11], and today's diet compositions can be either rich in carbohydrate or fat with RQ values closer to 1.0 or 0.7 respectively, the EE independence of RQ from Breezing device is very relevant to the field of energy expenditure assessment under free-living conditions.

In addition, considering that main stream of personal and professional practices use REE estimations from equations, such as the Harris-Benedict equation [3], which can produce a large error [12], Breezing® device is a practice' slow-cost and accurate alternative for personal and professional REE assessment.

As mentioned before, respiratory quotient is defined by [13]

$$RQ = V_{CO2} \, / \, V_{O2}, \tag{2}$$

And indicates primary source of energy metabolized (fat vs. carbohydrates) to generate energy for maintaining body functions and activities. Therefore, instruments that measure VO_2 alone [14] cannot provide RQ information. Breezing® can measure RQ with good accuracy (slope = 0.9939, R^2 = 0.9980 and Bland-Altman difference within ± 0.05 for 80% of the RQ values).

According to previous studies, the energy expenditure level can vary for the same people under different physical activity and diet conditions [15]. The sensing technology in Breezing® device was able to provide energy expenditure information to the study participants in a user-friendly manner guided by the cell phone app. Figure 3 shows an example of REE tracking for a study participant, who used Breezing® device under free living conditions several times in a day for a period of several days. As it can be seen, the new indirect calorimeter allows frequent monitoring of REE, and reveals theintrinsic REE value variability (~1,500 kcal/day average) of +/-10%, which has been reported to be typical for REE in the literature [11,16]. It is worth noticing, the study participant using the Breezing® device did not receive any professional assistance for the measurements' assessment..

Conclusion

The test results from Breezing® device show good agreement with the results from the Douglas Bag method for VO_2, VCO_2, EE and RQ. The EE readings from Breezing® show less than 10% difference with the readings from the Douglas bag method in the range of 1000 - 4000 kcal/day. Breezing® indirect calorimeter is a portable device and easy to use, which can benefit accurate assessment of energy expenditure for multiple clinical conditions such as Resting and Non-Resting conditions under free-living conditions, and related applications, such as weight management [16] and associated-energy expenditure changes [17], excess post-exercise oxygen consumption [11].

Acknowledgments

The authors acknowledge the study participants for compliance to protocols.

Conflict of interest

X. Xian, A. Quach, F. Tsow, E. Forzani and NJ Tao declare COI.

Authors' contributions

XX, EF, and NJ participated in the study design, data analysis, and manuscript preparation. XX, AQ, and DB participated in the recruitment of subjects, collection of the data. FT provided the technical support for the study.

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