Combined heart rate and activity improve estimates of oxygen consumption and carbon dioxide production rates

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Moon, J on K., and Nancy F. Butte. Combined heart rate and activity improve estimates of oxygen consumption and carbon dioxide production rates. J. Appl. Physiol. 81(4): 1754–1761, 1996.—Oxygen consumption (Vo2) and carbon dioxide production (Vco2) rates were measured by electronically recording heart rate (HR) and physical activity (PA). Mean daily Vo2 and Vco2 measurements by HR and PA were validated in adults (n = 10 women and 10 men) with room calorimeters. Thirteen linear and nonlinear functions of HR alone and HR combined with PA were tested as models of 24-h Vo2 and Vco2. Mean sleep Vo2 and Vco2 were similar to basal metabolic rates and were accurately estimated from HR alone (respective mean errors were –0.2 ± 0.8 (SD) and –0.4 ± 0.6%). The range of prediction errors for 24-h Vo2 and Vco2 was smallest for a model that used PA to assign HR for each minute to separate active and inactive curves (Vo2, –3.3 ± 3.5%; Vco2, –4.6 ± 3%). There were no significant correlations between Vco2 or Vco2 errors and subject age, weight, fat mass, ratio of daily to basal energy expenditure rate, or fitness. Vco2 and Vco2, and energy expenditure recorded for 3 free-living days were 5.6 ± 0.9 ml·min⁻¹·kg⁻¹, 4.7 ± 0.8 ml·min⁻¹·kg⁻¹, and 7.8 ± 1.6 kJ/min, respectively. Combined HR and PA measured 24-h Vo2 and Vco2 with a precision similar to alternative methods.

NUMEROUS STUDIES have demonstrated the potential for using heart rate (HR) and physical activity (PA) to estimate free-living metabolic rates. Electronically recording HR and PA is cheaper and less intrusive than calorimetric techniques. It also provides detailed information on daily activity patterns. However, several limitations of HR and PA monitoring have prevented their widespread use in clinical and nutritional studies. Until recently, electronic monitors were often uncomfortable, lacked resolution, and had limited data-storage capacity. Rapid advances in microcircuitry have made electronic monitors smaller, cheaper, and more powerful. Commercial devices are available that continuously record HR, PA, or both at resolutions of 1 min for several days.

Individual errors in measurement of energy expenditure (EE) by HR or PA can be quite large, as much as 30% for estimates of 24-h EE (1, 4, 8, 14). Group mean errors in the range of ±5% by HR monitoring have been higher than doubly labeled water, the current standard for the measurement of free-living EE (11).

The relationships of oxygen consumption (Vo2) rates to HR and PA are very different among individuals. For an individual, the relationships are complex and change with age, body composition, and fitness. Errors arise when the investigator chooses a mathematical function that does not accurately describe the nonlinear relationships of Vo2 to HR and PA.

Several models have been used to provide HR-based predictions of Vo2. Linear equations were used in the first attempts to predict Vo2 from HR (2). A model with two linear segments that intersect at an inactive-active (FLEX) HR threshold has proven the most popular (1, 4, 14). Several continuous nonlinear equations have also been proposed, including cubic, sigmoid, and logistic functions (2, 13).

This report addresses two questions. Does a 24-h calibration period of Vo2 and carbon dioxide production (Vco2) to HR and PA improve predictions of subsequent 24-h metabolic rates compared with previous efforts? Do nonlinear and discontinuous functions provide better models of the Vo2-to-HR and -PA relationships than a linear function of HR?

Three, approaches to modeling the relationships of Vo2 or Vco2 to HR and PA were evaluated. Method I modeled the relationships with a linear equation and five nonlinear equations based on HR alone. Method II combined PA with HR as independent variables in six nonlinear functions. Method III used a threshold level of PA to assign HR to separate active and inactive Vo2-to-HR functions.

METHODS

The study required 5 days of 24-h HR and PA recordings within a 1-wk period. On days 1 and 5, the subjects were confined to room calorimeters in the Metabolic Research Unit of the Children's Nutrition Research Center. Days 2–4 were free living, including normal work or school with no restrictions on activity. Written informed consent was obtained under a protocol approved by the Baylor College of Medicine Review Board for Human Subject Research.

Subjects

Twenty Houston-area adults (19–40 yr) volunteered for the study. Equal numbers of sedentary and active individuals were selected to represent a range of fitness levels. Volunteers were nonsmokers, had a body mass index < 26, and were not taking prescription medication other than birth control. One subject was a vegetarian.

Weight (491KL, Healthometer, Bridgeview, IL) and body composition (HA-2, EM-Scan, Springfield, IL) were measured on the morning the subjects left the calorimeter after a 12-h fast. Peak Vo2 (Vo2peak) was estimated in the calorimeter from HR and Vo2 during moderate stationary cycle exercise with the equation Vo2peak = (600 – age – b)/HR – b, where b = 73 for the women and 63 for the men (10).

HR Recording

HRs were collected at 1-min intervals on each day of the study. Electrodes (LRM306, Lead-lock, Sandpoint, ID) were applied after the skin was cleaned with alcohol. On study...
days 1 and 5 (in the calorimeter), HR was recorded by telemetry as the total number of cardiac cycles each minute (DS-3000, Fukuda Denshi, Tokyo, Japan). The transmitter was clipped on the belt or waistband. On free-living days (days 2–4), HR was recorded with a battery-powered transmitter worn on the chest and a wristwatch storage unit (Vantage XL, Polar Electro, Kempele, Finland).

Activity Recording

PA was recorded at 16-s intervals as counts from a vibration sensor (Act I, Mini-mitter, Sun River, OR). The sensor was securely taped on the outside of the dominant leg.

Calorimeter Procedures

Measurements of \( V_{O2} \) and \( V_{CO2} \) over 24 h were performed on days 1 and 5 in 31-m\(^2\) room calorimeters (9). A treadmill (905E, Precor, Bothell, WA), cycle ergometer (Corval 400, Lode, Groningen, The Netherlands), 10-cm step platform, and metronome were added to the calorimeter equipment. Calorimeter temperature was set at 24°C, relative humidity was 30–50%, and the carbon dioxide concentration was controlled to 0.45% by regulating the inflow.

Calorimeter tests began at 0800. Meals were served at 0830, 1200, and 1700, and a snack was served at 1800. The meals provided 12.1 kJ for the men and 9.2 kJ for the women as 49% carbohydrate, 32% fat, and 19% protein. The subjects were allowed only water after 1900.

Day 1 calibration of HR and PA to metabolic rate included two sessions of compulsory activities. The morning session, which began at 0900, consisted of 30 min of supine rest, 20 min of seated rest, 5 min of seated timed respiration, 15 min of standing, and two levels of cycle exercise for 15 min at workloads intended to produce 50 and 75% of the estimated peak HR. The afternoon activities were 15-min periods of seated writing, walking around the room, and three levels of treadmill exercise at 1 m/s and 50 and 75% of peak HR, beginning at 1300. A 15-min step test was added to the afternoon exercise routine beginning with subject 4. Exercise was halted if \( V_{O2} \) exceeded 80% of \( V_{O2 \text{peak}} \) or if the HR exceeded 180 beats/min for >2 min. The compulsory activities totaled ~4 h. For the rest of the day, the subjects were allowed free choice of activities. The subjects were not allowed to nap until they went to sleep at night. They were awakened by 0710 and remained supine for 40 min to estimate basal metabolic rates (BMRs).

On day 5, the subjects chose the type of exercise (cycle, treadmill, aerobics, etc.) and duration (at least 20 min). A minimum workload or speed was assigned to approximate moderately heavy exercise. The subjects were allowed to exceed the assigned minimums.

Free-Living Procedure

Free-living HR and PA were recorded for 24 h on days 2–4. Days 2 and 3 were identified as “weekdays” when the subject went to work or otherwise engaged in activities that generally represented their schedule for 4 or more days each week. Day 4 was designated “weekend.” Recordings were interrupted only for bathing or showers. The PA monitor was removed during swimming, but the HR recording was maintained with the storage unit sealed in a plastic bag and placed in the swimsuit. Data from the HR and PA monitors were copied to a computer each morning.

Prediction Models of \( V_{O2} \) and \( V_{CO2} \) from HR and PA

Activity data were collapsed from 16-s to 1-min intervals. Twenty-four-hour records of HR, PA, \( V_{O2} \), and \( V_{CO2} \) were examined for proper alignment. Short periods (5 min or less) of HR and PA data that were missing or contained obvious artifacts were replaced with a prior value. Longer periods of corrupted data caused by loss of recording or electrical interference were removed from analysis. Sleep and awake periods were determined by inspection of HR and PA records for a rapid decline in HR followed by >1 h of minimal HR and PA close to zero.

Method I: HR Regression

The first series of models evaluated the accuracy of one linear and five nonlinear functions based on HR alone (Eqs. 1–6). \( a, b, c, \) and \( d \) are coefficients. In Eq. 6, \( e \) represents the natural logarithm base, not a coefficient. Three datasets were prepared from day 1: 24 h, awake, and sleep. \( V_{O2} \) and \( V_{CO2} \) were fitted by regression to HR for each data set. With six functions and three data sets, a total of 18 regressions were performed for each subject.

Linear \( V_{O2} \) or \( V_{CO2} = a + b \cdot HR \) (1)

HR \(^2\) \( V_{O2} \) or \( V_{CO2} = a + b \cdot HR^2 \) (2)

HR \(^3\) \( V_{O2} \) or \( V_{CO2} = a + b \cdot HR^3 \) (3)

Power \( V_{O2} \) or \( V_{CO2} = a + b \cdot HR^c \) (4)

Logistic \( V_{O2} \) or \( V_{CO2} = a + b/(1 + (HR/c)^e) \) (5)

Sigmoid \( V_{O2} \) or \( V_{CO2} = a + b/[1 + e^{(HR/c)}] \) (6)

Method II: HR and Activity

Day 1 data again were separated into 24-h awake and sleep periods. PA data from both days were low-pass filtered to match the dynamics of \( V_{O2} \) and \( V_{CO2} \) by calculating an adjusted PA* with Eq. 7. The coefficients \( a \) and \( b \) in Eq. 7 were determined by iteration to maximize the linear correlation of PA to \( V_{O2} \) and \( V_{CO2} \). Two sets of values for \( a \) and \( b \) were calculated separately to fit awake and sleep \( V_{O2} \) and \( V_{CO2} \), and were constrained to be >0 and <1. The symbol PA* in Eq. 7 represents the value of PA* calculated for the previous minute.

\[
PA* = a \cdot PA*_{-1} + (1 - a) \cdot PA \quad \text{for} \quad PA \geq PA*_{-1}
\]

\[
PA* = b \cdot PA*_{-1} + (1 - b) \cdot PA \quad \text{for} \quad PA < PA*_{-1}
\]

Awake \( V_{O2} \) and \( V_{CO2} \) were combined with HR and PA in multiple regression functions (Eqs. 8–13). \( f, g, \) and \( h \) are coefficients. Mean regression statistics were assembled for each equation across all subjects. The best fit equations were used to estimate \( V_{O2} \) and \( V_{CO2} \) on day 5. For minutes where \( PA* \) data were missing, a similar equation from method I based on HR alone was used.

\[
V_{O2} = a + b/(1 + (HR/c)^d) + h/[1 + (PA*^f)^g]
\]

\[
V_{O2} = a + b/(1 + (HR/c)^d) \cdot h/[1 + (PA*^f)^g]
\]

\[
V_{O2} = a + b \cdot HR^3 + c \cdot PA^{0.5}
\]

\[
V_{O2} = a + b \cdot HR^{2.5} + c \cdot PA^{0.5} \ln PA*
\]

\[
V_{O2} = a + b \cdot HR^{2.5} + c \cdot PA
\]

\[
V_{O2} = a + b \cdot HR^{2.5} + c \cdot PA^{0.5}
\]
Method III: Awake Separated Into Active and Inactive Periods

The 24-h records of day 1 \( \dot{V}O_2 \) and \( \dot{V}CO_2 \) were separated into awake and sleep segments by inspection of HR and PA as in Method I: HR Regression and Method II: HR and Activity. Awake periods were further separated into active (standing and exercise) and inactive segments (awake exclusive of standing, exercise, and 1- or 1.5-h postexercise ergometer and treadmill, respectively). HR3 regressions were fitted to inactive \( \dot{V}O_2 \) and \( \dot{V}CO_2 \). Linear regression of HR on active \( \dot{V}O_2 \) and \( \dot{V}CO_2 \) was performed for V˙O2. To be classified as active, each minute required a HR above the threshold and PA had to exceed the threshold during the current minute or either of the 2 previous min \( [PA(-2,-1,0)] \) in Eq. 14.

\[
\dot{V}O_2 = a + b\cdot HR^3
\]

Inactive: \( \dot{V}O_2 = c + d\cdot HR \), Active: \( \dot{V}O_2 = a + b\cdot HR^3 \)

V˙O2 and V˙CO2 for each minute of days 2–5 were estimated from inactive HR unless both PA and HR exceeded fixed thresholds (Eq. 14 for V˙O2). In Eq. 14, PA and HR denote the threshold levels for that individual. The PA threshold was calculated on day 1 as the median PA from either walking or the slowest treadmill exercise (whichever was lower). The HR threshold was the intersection of the inactive and active equations for V˙O2. To be classified as active, each minute required a HR above the threshold and PA had to exceed the threshold during the current minute or either of the 2 previous min \( [PA(-2,-1,0)] \) in Eq. 14.

Statistical Analysis

Data are summarized as means ± SD. Differences between group means for men and women (by weight, body composition, 24-h EE/BMR, V˙O2peak, and age) were evaluated for significance by one-way analysis of variance. Differences within individuals between test days (HR and sleep time) were evaluated by paired t-test. The various V˙O2 and V˙CO2 prediction errors were compared by multiple regression that included weight, body composition, 24-h EE/BMR, V˙O2peak, and age as independent variables. Significance was assessed on the regression residuals. For all tests, the null hypothesis was rejected at \( P \leq 0.05 \).

PA* was calculated by numeric iteration with a conjugate search at a precision of 0.01 and tolerance of 5% (Excel 4.0, Microsoft, Redmond, WA). Nonlinear regression of V˙O2 and V˙CO2 on HR (Eqs. 2–6) was performed by singular-value decomposition (TableCurve 2D, Jandel Scientific, San Rafael, CA). Multiple nonlinear regression of HR and PA (Eqs. 8 and 13) used Gaussian elimination with a convergence precision of 6 and a linear significance of 0.1% (TableCurve 3D, Jandel). Regression equations were evaluated primarily by a modified F-statistic (calculated by TableCurve) that provided better discrimination than \( R^2 \) because it imposed a cost on increasing model complexity (order).

RESULTS

The men were older (32 ± 5 vs. 28 ± 8 yr) and heavier (74 ± 7 vs. 59 ± 7 kg) and had a higher estimated V˙O2peak (43 ± 10 vs. 37 ± 8 ml·kg⁻¹·min⁻¹) but a similar fat mass (14 ± 5 vs. 15 ± 2 kg) compared with the women. All 20 subjects completed the calorimeter portion (days 1 and 5) of the study. Mean record durations for HR, PA and V˙O2 on day 1 were 1,440 ± 0, 1,400 ± 167, and 1,440 ± 0 min, respectively. Missing PA data for one subject on day 1 occurred during sleep and did not affect the analysis. Excluding this subject, the average PA record was 1,437 ± 7 min. PA data from day 5 for two subjects could not be analyzed.

There was no significant change in the subjects’ weight (\( P = 0.2 \)) from day 1 to day 5. Subjects slept less (436 ± 78 min; 30.3% on day 1 than on day 5 (489 ± 66 min; 33.9%); paired difference \( P = 0.02 \). Other differences between day 1 and day 5 measurements are summarized in Table 1. Mean ratios of 24-h V˙O2 to basal V˙O2 were 1.68 ± 0.15 (range 1.33–1.96) on day 1 and 1.69 ± 0.17 (range 1.36–1.95) on day 5.

Data were analyzed for 55 of the 60 free-living days planned for the study. At least two free-living records were obtained for each subject. Daily free-living records of HR and PA in each 24-h period averaged 1,373 ± 192 (93%) and 1,389 ± 140 min (96%), respectively. Most often, the subjects experienced interrupted HR recording during sleep on the first night. Further instructions to the subjects reduced data loss on subsequent nights. Data lost during sleep had little effect on subsequent analyses. Total awake and sleep records averaged 950 ± 104 and 448 ± 129 min, respectively.

Metabolic Rate Measurements

Method I. 24-h \( R^2 \) values for the nonlinear equations (Eqs. 2–6, \( R^2 = 0.86–0.91 \)) were better than those for Eq. 1 (\( R^2 = 0.77 \)). There were no significant differences in 24-h awake or sleep \( R^2 \) values among any regressions involving nonlinear equations. HR3 (Eq. 3) had the highest values for the F-statistic so that it was probably the most computationally efficient model of the data.
Table 1. Mean \( \dot{V}_{O_2} \), \( \dot{V}_{CO_2} \), and HR for 24 h, awake, 30-min BMR and nightime sleep in a room calorimeter and free living

<table>
<thead>
<tr>
<th></th>
<th>Calorimeter</th>
<th>FreeLiving</th>
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<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 5</td>
</tr>
<tr>
<td>24 h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EE, kJ/min</td>
<td>7.38 ± 1.44</td>
<td>7.37 ± 1.43</td>
</tr>
<tr>
<td>( \dot{V}_{O_2} ), l/min</td>
<td>0.36 ± 0.07</td>
<td>0.36 ± 0.07</td>
</tr>
<tr>
<td>( \dot{V}_{CO_2} ), l/min</td>
<td>0.31 ± 0.06</td>
<td>0.31 ± 0.06</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>73 ± 8.5</td>
<td>70 ± 9.4*</td>
</tr>
<tr>
<td>Awake</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EE, kJ/min</td>
<td>9.14 ± 1.85</td>
<td>9.2 ± 1.83</td>
</tr>
<tr>
<td>( \dot{V}_{O_2} ), l/min</td>
<td>0.44 ± 0.09</td>
<td>0.45 ± 0.09</td>
</tr>
<tr>
<td>( \dot{V}_{CO_2} ), l/min</td>
<td>0.38 ± 0.08</td>
<td>0.39 ± 0.08</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>82 ± 9</td>
<td>78 ± 10*</td>
</tr>
<tr>
<td>Duration, min</td>
<td>898 ± 53</td>
<td>913 ± 67</td>
</tr>
<tr>
<td>BMR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EE, kJ/min</td>
<td>4.29 ± 0.54</td>
<td>4.23 ± 0.58</td>
</tr>
<tr>
<td>( \dot{V}_{O_2} ), l/min</td>
<td>0.21 ± 0.03</td>
<td>0.21 ± 0.03</td>
</tr>
<tr>
<td>( \dot{V}_{CO_2} ), l/min</td>
<td>0.17 ± 0.02</td>
<td>0.15 ± 0.02</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>61 ± 11</td>
<td>58 ± 10*</td>
</tr>
<tr>
<td>Duration, min</td>
<td>436 ± 78</td>
<td>489 ± 66*</td>
</tr>
</tbody>
</table>

Values are means ± SD. \( \dot{V}_{O_2} \), \( \dot{V}_{CO_2} \), HR, BMR, EE. Values are in percent. See text of description of methods I, II, and III and Eqs. 3, 11, and 14.

(see text). EE was calculated from measured \( \dot{V}_{O_2} \) and physical activity by method III (see text). EE was calculated from \( \dot{V}_{O_2} \) and \( \dot{V}_{CO_2} \) by nonprotein equation of de V Weir (3). *Significant difference between calorimeter days, \( P < 0.05 \).

Table 2. Awake \( \dot{V}_{O_2} \) and \( \dot{V}_{CO_2} \) estimate errors relative to measurements in a room calorimeter

<table>
<thead>
<tr>
<th></th>
<th>HR (method I, Eq. 3)</th>
<th>HR and Activity (method II, Eq. 11)</th>
<th>HR Functions Assigned by Activity (method III, Eq. 14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{V}_{O_2} )</td>
<td>( \dot{V}_{CO_2} )</td>
<td>( \dot{V}_{O_2} )</td>
<td>( \dot{V}_{CO_2} )</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>−5.9 ± 8.3</td>
<td>−7.8 ± 10.7</td>
<td>−4.4 ± 6.6</td>
</tr>
<tr>
<td>Range</td>
<td>−21.9 to 9.2</td>
<td>−23.7 to 22.6</td>
<td>−13.8 to 10.6</td>
</tr>
</tbody>
</table>
the calorimeter from walking, cycling, treadmill exercise, and the step test. Steady-state exercise averaged $11.0 \pm 1.9$ min (Fig. 3).

Errors of estimated $\dot{V}O_2$ and $\dot{V}CO_2$ during awake periods were $2.3 \pm 3.4$ and $2.4 \pm 4.5\%$, respectively (Table 2). During active periods, errors in estimated $\dot{V}O_2$ and $\dot{V}CO_2$ were $2.2 \pm 8.1$ and $2.3 \pm 8.4\%$, respectively. One subject had substantially higher predicted $\dot{V}O_2$ and $\dot{V}CO_2$ (26 and 28%, respectively) during a single exercise session. Means $\pm SD$ for active periods recalculated with this subject excluded were lower ($\dot{V}O_2, 2.3 \pm 4.1\%$; $\dot{V}CO_2, 4.1 \pm 3.6\%$). Inactive mean estimations contributed the most error ($\dot{V}O_2, -4.3 \pm 5.5\%$; $\dot{V}CO_2, -6.3 \pm 5.4\%$). We did not find any significant relationships between awake $\dot{V}O_2$ or $\dot{V}CO_2$ prediction errors and subject fitness (estimated $\dot{V}O_2peak$), age, weight (Fig. 2B), lean tissue mass, or 24-h EE/BMR (from day 1 data). Twenty-four-hour measured $\dot{V}O_2$ and $\dot{V}O_2$ predicted by method III are compared for one subject in Fig. 4.

Free-living measurements. Sleep estimates of $\dot{V}O_2$ and $\dot{V}CO_2$ were obtained with HR$^3$ (Eq. 3) developed in method I, and predictions for the awake periods used method III (Eq. 14). None of the differences between days 2 and 3 (weekdays) and day 4 (weekend) were significant. The mean 24-h $\dot{V}O_2$ and $\dot{V}CO_2$ values on all 3 free-living days were $0.01 \pm 0.06$ and $0.008 \pm 0.06$ l/min greater, respectively, than on day 1 in the calorimeter (Table 1).

**DISCUSSION**

Method III achieved improved precision in $\dot{V}O_2$ estimates by the classification of awake HR to active and inactive functions by using PA. The active HR function was calculated as a linear function with measurements made during exercise (Eq. 14). Inactive periods were estimated with a cubed function of HR during periods with low PA levels. For much of the day, our subjects confined themselves to relatively sedentary activities characterized by a limited range of $\dot{V}O_2$ over a moderate range of HR. Most individuals displayed a range of HR with both higher and lower $\dot{V}O_2$ that was matched by the two functions in the model (Fig. 1B).

Dauncey and James (2) were the first to evaluate HR monitoring against 24-h measurements of $\dot{V}O_2$ in a room calorimeter. They tested several models for the $\dot{V}O_2$-HR relationship, including linear, logistic, and power functions, and recommended that future efforts explore nonlinear equations to describe $\dot{V}O_2$ to HR as continuous functions. They also looked forward to the development of room calorimeters capable of faster measurements.

We found the 24-h calibration period to be valuable in two respects. First, it correctly weighted the predominant sedentary periods in the regression algorithms. Second, it allowed us to define sections of lower $\dot{V}O_2$ and moderate HR that did not correspond to any compulsory
activities or exercise. These VO₂-HR combinations appeared throughout the day but were most prolonged during recovery from exercise.

Large calorimeters can now be operated with response times of <5 min (9) and have been used by others for calibration of EE-HR relationships (8). We scheduled 15 min for compulsory activities to allow time for the calorimeter and subject to reach a steady state. An average of 11.0 ± 1.9 min of steady-state data were analyzed from each 15-min interval (Fig. 3).

Mean 24-h VO₂ on day 5 was 0.36 l/min or 1.7 times the measured basal VO₂. Twenty-four-hour VO₂ and VCO₂ in the calorimeter (days 1 and 5) averaged 5.4 and 3.9%, respectively, lower than the mean free-living VO₂ and VCO₂ (days 2–4). Mean indexes of physical activity (PAI = 24-h EE/BMR) in the calorimeter (1.68 ± 0.15, range 1.33–1.96) were similar to free-living days (1.73 ± 0.31, range 1.3–2.7), although the free-living range was greater. The free-living PAI for the men (1.78 ± 0.26) was not significantly higher than that for the women (1.68 ± 0.36; P = 0.4). The PAI values for both sexes were within the ranges reported by others (1, 8, 12). Schulz and Schoeller (12) reported a higher PAI for a large number of men (1.84 ± 0.31) and women (1.7 ± 0.23) and noted that these values were higher than the recommended dietary allowances.

R² values of all HR functions to VO₂ and VCO₂ during sleep were low (0.15–0.21). PA signals were minimal because slight motions fell below the threshold of the PA sensor. Yet, predictions of VO₂ because slight motions fell below the threshold of the PA sensor. Yet, predictions of VO₂ and VCO₂ were adequately predicted by regressions across sub-

2 values of all HR functions to VO₂ and VCO₂ during sleep were low (0.15–0.21). PA signals were minimal because slight motions fell below the threshold of the PA sensor. Yet, predictions of VO₂ and VCO₂ were adequately predicted by regressions across sub-

jects and lower than during any exercise.

The range of errors in predicting day 5 awake VO₂ by method III was from −10.6 to 4.6% (16% overall). Only a few recent studies have compared HR techniques with room calorimetry, and all used the FLEX method. Reported overall error ranges were 20 and 35% for adult studies (1, 14) and only 10% in children (4). In addition, 24-h HR monitoring has been validated against the doubly labeled water method, with error ranges of 40% or more (9, 13, 7). Doubly labeled water has performed well in comparisons with calorimetry. In a published summary of several validation studies, labeled-water tests in adults had a weighted mean error <1% and a mean SD of 7% (12).

In method III, an average of 251 ± 196 min were above the threshold HR but below the PA threshold and were thus classified as inactive. Redefining all these points as active, as would occur with a method employing HR alone, would have increased the awake mean VO₂ and VCO₂ to produce estimation errors of 5.3 ± 8.6 and 3.5 ± 7.4%, respectively. One subject's VO₂ and VCO₂ were clearly overestimated by this simulated adjustment (errors: VO₂, 30%; VCO₂, 24%). With this subject removed, the mean estimation errors were still elevated (VO₂, 4 ± 6.6%; VCO₂, 2.4 ± 5.9%). The threshold HR was similar to mean 24-h HR for most subjects and lower than during any exercise.

Errors in HR estimation of metabolic gas exchange may arise from inadequate calibration data, poor modeling of the VO₂ and VCO₂ relationships to HR, and uncompensated effects on HR, stroke volume, and oxygen extraction. Day-to-day intraindividual variations in the VO₂-HR characteristic may exceed 10% (7). Over longer periods, the VO₂-HR relationship is altered by growth, aging, and changes in fitness or body composition. Our results confirmed the importance of calibrating VO₂ to HR for each individual. Frequent
recalibration may be needed in studies that involve physical training or changes in weight.

None of the differences between individuals in weight, lean tissue mass, VO₂peak, age, or PAI helped to explain errors in prediction of VO₂ and VCO₂. The effect of weight on methods I and III is shown in Fig. 2. Lean tissue mass is correlated with weight and gives similar results. All the subjects were healthy sedentary adults from 20 to 40 yr so that age was unlikely to be related to growth, overall health, or activity. The lack of a relationship between VO₂peak or PAI and measurement error suggests that the 24-h period of calibration compensated for the variation in levels of habitual activity.

Mean day 5 prediction errors for VO₂ and VCO₂ were lower for method III than for methods I and II. One explanation might be that HR was elevated because of anxiety or some other cause during onimposed exercises on day 1. Method III eliminated data during recovery from bicycle and treadmill exercise. HR recorded during the steady-state portion of exercise may have been more closely driven by metabolic demand. Li et al. (8) observed a similar phenomenon that led to their recommendation that calibration be performed with exercises that match a subject’s normal activities.

Predicted mean VO₂ and VCO₂ on day 5 for all three methods were significantly lower than the mean VO₂ and VCO₂ as measured by the calorimeters. Mean 24-h and awake HR and PA values were significantly lower on day 5 than on day 1 (Table 1). However, there was no significant difference in EE, VO₂, VCO₂, or the ratio of 24-h VO₂ to BMR VO₂ between day 1 and day 5. The subjects slept longer on day 5 than on day 1, but awake HR was lower, as well as 24-h HR. Confinement to the calorimeter, exposure to an unusual workout, and more intense scrutiny during calibration may have caused anxiety and elevated HR on day 1, leading to an underestimate on day 5.

Li et al. (7) proposed many other sources of short-term intradividual differences in VO₂-to-HR relationships, including infection, sleep (quality and duration), temperature, emotion, alcohol/caffeine/cigarette consumption, or meal timing. Most of these factors were eliminated in this study. The calorimeter temperature differed <1°C between day 1 and day 5. The subjects were not permitted alcohol or cigarettes, and caffeine consumption was minimal. Meals and meal times were identical. None of the subjects had abnormal body temperatures when they entered the calorimeters, and no one complained of illness at any time during the study.

All three methods underestimated VCO₂ by a greater percentage than VO₂ but with lower SDs. In addition to the HR and exercise effects discussed above, VCO₂ may have differed on day 5 relative to day 1 because of altered rates of substrate oxidation. The mean 24-h respiratory quotient (VCO₂/VO₂) was slightly higher on day 5 (0.86) than on day 1 (0.85; P = 0.016). There were no significant differences in respiratory quotient during sleep or BMR measurement. Relative differences in VO₂ and VCO₂ may have occurred because subjects altered their substrate intakes by choosing to eat different portions of their meals.

Most equations to estimate EE from VO₂ and VCO₂ can be reduced to linear combinations of the two parameters, with VO₂ making a much larger contribution than VCO₂. For example, in the nonprotein equation of de V Weir (3), the contribution of VO₂ is 3.5 times greater than that of VCO₂. Measurement errors from VO₂ and VCO₂ contribute to errors in EE in the same proportion. Thus estimates of EE are unlikely to be improved by measurement of VCO₂ from HR. However, if VCO₂ is of interest separately, it might be beneficial to supplement the HR recording with a dietary record.

Conclusions

The precision of VO₂ and VCO₂ predictions was improved by combining PA monitoring with electronically recorded HR. PA data were most effective when used to assign HR to separate active and inactive VO₂ and VCO₂ prediction functions than when entered simultaneously with HR in nonlinear equations. In the present group of healthy adults, the HR and PA method produced results similar to other techniques available for free-living measurements (−3.3 ± 3.5 and −4.6 ± 3.6% for 24-h VO₂ and VCO₂, respectively). Further efforts should be made to resolve the underestimation of VO₂ and VCO₂.

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