Validity of inspiratory and expiratory methods of measuring gas exchange with a computerized system

DAVID R. BASSETT, JR., EDWARD T. HOWLEY, DIXIE L. THOMPSON, GEORGE A. KING, SCOTT J. STRATH, JAMES E. McLAUGHLIN, AND BRIAN B. PARR

Department of Exercise Science and Sport Management, University of Tennessee, Knoxville, Tennessee 37996-2700

Received 22 September 2000; accepted in final form 9 February 2001

Bassett, David R., Jr., Edward T. Howley, Dixie L. Thompson, George A. King, Scott J. Strath, James E. McLaughlin, and Brian B. Parr. Validity of inspiratory and expiratory methods of measuring gas exchange with a computerized system. J Appl Physiol 91: 218–224, 2001.—The accuracy of a computerized metabolic system, using inspiratory and expiratory methods of measuring ventilation, was assessed in eight male subjects. Gas exchange was measured at rest and during five stages on a cycle ergometer. Pneumotachometers were placed on the inspired and expired side to measure inspired (V˙I) and expired ventilation (V˙E). The devices were connected to two systems sampling expired O₂ and CO₂ from a single mixing chamber. Simultaneously, the criterion (Douglas bag, or DB) method assessed V˙E and fractions of O₂ and CO₂ in expired gas (FEO₂ and FECO₂) for subsequent calculation of O₂ uptake (V˙O₂), CO₂ production (V˙CO₂), and respiratory exchange ratio. Both systems accurately measured metabolic variables over a wide range of intensities. Though differences were found between the DB and computerized systems for FEO₂ (both inspired and expired systems), FECO₂ (expired system only), and V˙O₂ (inspired system only), the differences were extremely small (FEO₂ = 0.0004, FECO₂ = −0.0003, V˙O₂ = −0.018 l/min). Thus a computerized system, using inspiratory or expiratory configurations, permits extremely precise measurements to be made in a less time-consuming manner than the DB technique.

Douglas bag; oxygen uptake; carbon dioxide production; metabolism; pneumotachometer

The measurement of O₂ consumption (V˙O₂) by open-circuit spirometry is one of the fundamental measures in the field of exercise physiology. Historically, gas exchange was measured by the Douglas bag method. This involved the collection of exhaled air in large, impermeable canvas bags and subsequent measurement of gas fractions and expired volumes (4). The Douglas bag method has served as the “gold standard” for gas exchange measurements for over a century.

In the 1960s, with the development of the Parkinson-Cowan dry gas meter, the measurement of inspired minute ventilation (V˙I) became common. Expired ventilation (V˙E) values were calculated using the Haldane transformation of the Fick equation (5, 6, 13). In the semiautomated method described by Wilmore and Costill (20), the measurement of FEO₂ and FECO₂ in expired air was achieved by drawing representative gas samples from a mixing chamber into 2-liter latex bags for subsequent analysis. In this application, the expired gas was collected over the same time period as V˙I was measured to ensure matching of gas fractions and the ventilatory volumes. A later method involved pumping a continuous stream of exhaled air from a mixing chamber directly into electronic gas analyzers (1). The voltage output of the gas analyzers and inspired ventilation meter was fed through an analog-to-digital converter into a microcomputer, which carried out the metabolic calculations for O₂ uptake (V˙O₂) and CO₂ production (V˙CO₂) (1). Because of the lag time associated with drying and analysis of the gas, timing adjustments had to be made to assure matching of the gas volume with its gas fractions (14).

Today, most computerized metabolic systems measure the ventilation rate on the expired side. One advantage of this method is that the subject can be connected to the metabolic cart by means of a single expired-gas hose. A common method of measuring V˙E is with the use of the Hans Rudolf 3813 pneumotachometer (Kansas City, MO) that was designed to have flow linearity in the range of 0–800 l/min (peak flow rates). It consists of a series of three screens that create a resistance to airflow. The drop in air pressure across the center screen is used to compute the gas flow rate. However, the Hans Rudolf pneumotachometer is non-linear in the lower flow range (<80 l/min). Hence, the Yeh algorithm (22, 23) is used to further correct the linearity at low flow rates (<80 l/min) and to assess any change in resistance created by the upstream geometry or changes in gas viscosity (e.g., helium-O₂ mixtures used in some studies).

The use of a pneumotachometer for measurement of V˙E, as opposed to V˙I, has certain problems associated with it. The principal concern is condensation of water vapor on the screen, due to the moisture present in exhaled air. To eliminate this concern, Hans Rudolf...
developed a heated pneumotachometer (model 3813) that prevents condensation. However, this device increases the temperature and therefore the volume of gas passing through it (8). Various methods have been proposed to estimate the temperature of the gas as it passes through the screen, so that ventilation rates can be converted to reflect standard temperature and pressure, dry (STPD) conditions. One method, derived from the work of Kolkhorst et al. (8), is to average the ambient temperature with body temperature (37°C). Little information exists regarding the validity of this averaging method for determining the expired gas temperature.

In recent years, indirect calorimetry has largely become an automated procedure; hence, it is important to establish the accuracy with which gas exchange measurements are made. The purpose of this study was to validate the measurement of gas exchange using a computerized metabolic system, with either \( V\dot{I} \) or \( V\dot{E} \) measurement. Ventilatory and metabolic variables were compared with the classical Douglas bag technique, which served as the criterion method.

**METHODS**

**Participants.** Eight male university students volunteered to participate in the study. The nature of the study was described, and they signed a written, informed consent statement in accordance with the policies of the university’s institutional review board. Physical characteristics of the participants were recorded (means ± SD: age = 27.5 ± 5.6 yr, height = 181.8 ± 3.3 cm, weight = 74.9 ± 7.1 kg).

**Experimental design.** The exercise protocol was preceded by 10 min of seated rest on a Monark 818E cycle ergometer (Varburg, Sweden). Participants then performed a graded exercise test consisting of 5-min stages at power outputs of 50, 100, 150, 200, and 250 W. Before testing, the cycle ergometer was calibrated by placing it on a level surface and placing known weights (1–4 kg) on the disconnected flywheel belt, while adjusting the position of the pendulum arm to reflect these settings. An electronic metronome was used to keep the participant’s cadence at 51 rpm throughout the test.

Each subject was fitted with a rubber mouthpiece connected to a Hans Rudolf 2700 series two-way nonrebreathing valve (Kansas City, MO). A nose clip was worn to prevent nasal breathing. The breathing valve was connected to the metabolic systems on the inspired and expired sides with 2-m corrugated flexible plastic hoses with a 3.2-cm diameter.

Continuous gas exchange measurements were made by using two TrueMax 2400 computerized metabolic systems purchased from the same manufacturer (ParvoMedics, Salt Lake City, UT). The software version was Consentius OUSW-3.3. Both systems utilized the Hans Rudolf 3813 pneumotachometer to measure ventilation. However, one of these systems was set up to measure \( V\dot{I} \), whereas the other was set up to measure \( V\dot{E} \) (see Fig. 1). The pneumotachometer on the expired side was heated to a temperature of 37°C, while the heater on the inspired side was turned off by unplugging the heater cable from the back of the unit. The expired gas temperature was assumed to be the average of body temperature (37°C) and ambient temperature. A Y-connector was used to join the two gas sampling lines to the mixing chamber. For each system, expired gas fractions were determined by drawing a continuous sample of expired air from the mixing chamber through a 61-cm Naef Dryer (Permapure, Toms River, NJ) catheter into a paramagnetic \( O_2 \) analyzer and infrared \( CO_2 \) analyzer.

Expired air was collected in meteorological balloons during the last 5 min of rest and during the last 2 min of each 5-min exercise stage. A three-way 3900 series Hans Rudolf Y-stopcock and meteorological balloon were placed in series with the mixing chamber used by the computerized metabolic systems. This allowed for simultaneous measurement of gas exchange via both metabolic systems and the Douglas bag method. At the end of each sampling period, the gas fractions in the meteorological balloons were measured using a Beckman LB2 \( CO_2 \) analyzer (Schiller Park, IL) and Applied Electrochemistry S-3A \( O_2 \) analyzer (Sunnyvale, CA). The gas concentrations were determined while the next stage was being performed (i.e., within 5 min). The expired volume was then determined by pushing the collected gas through a 120-liter Tissot gasometer (Warren E. Collins, Braintree, MA). Corrections were made for the small volume of air removed for gas analysis, which included the gas sampled from the meteorological balloons (0.6 liter) and the gas removed by the two ParvoMedics systems (0.69 l/min).

All three sets of gas analyzers were calibrated using 1) room air and 2) a single gas tank (15.09% \( O_2 \), 6.01% \( CO_2 \)) that had previously been analyzed by the micro-Scholander technique (15). Another gas tank (17.99% \( O_2 \), 2.99% \( CO_2 \)) was used to ensure linearity of the analyzers across the physiological range. The computerized metabolic systems were calibrated with a 15-stroke calibration of a 3.00-liter Hans Rudolf 5530 series syringe. This was readjusted periodically (after every two or three subjects) by using a five-stroke calibration. Ambient temperature (\( T_a \)) and barometric pressure (\( P_b \)) were measured at the start of each test, and these data were entered into the computers.
For all three methods, VO2 was calculated by using the respiratory Fick principle. Where VE was measured, Vt was computed from the so-called Haldane transformation (5, 6): 
\[ Vt = \frac{VE \times FEnO / FInO}{1 - FEnO} \]
where FEnO and FInO equal the fractional concentrations of nitrogen in the expired and inspired air, respectively. Likewise, in the method in which inspired ventilation was measured, the expired ventilation was computed using the same formula. These methods assume that N2 is neither produced nor consumed by the body in exercise, an assumption that had previously been questioned by Cissik et al. (3) but was later examined by Wilmore and Costill (19) and found to be valid.

**Data analysis.** The dependent variables of VE STPD, FEo2, FEco2, VO2, VC02, and respiratory exchange ratio were examined at all power outputs, for each of the three methods. Bland-Altman (2) plots were used to show the individual differences between the criterion method (Douglas bag) and the inspired or expired computerized metabolic systems.

Statistical analyses were carried out by use of two-way repeated measures ANOVAs (method × power output) for each of the dependent variables, using SPSS for Windows release 9.0.0 1998 (SPSS, Chicago, IL). Because some subjects were unable to perform exercise at 250 W, only five power outputs (0, 50, 100, 150, and 200 W) were analyzed. The two ANOVAs we performed compared 1) inspired metabolic cart to the Douglas bag method and 2) expired metabolic cart vs. the Douglas bag method. This was justified by the purpose of the study, which was to determine whether each computerized method was valid compared with the criterion. For those subjects who were able to complete the 250 W stage, a separate ANOVA was done to compare the three methods for the last level. The significance level was set at 0.05 for all comparisons. Bonferroni adjustments were carried out for each variable to account for multiple comparisons.

**RESULTS**

Table 1 shows the physiological responses to a graded exercise test on a cycle ergometer. Data are expressed as means ± SD. The computerized system (using inspiratory or expiratory ventilation measures) showed close agreement with the Douglas bag method for all of the gas exchange variables. Where significant differences did exist, the magnitude of the differences was very small. For instance, FEo2 was slightly lower (by an average of 0.0004 or 0.04%) for both inspired and expired computerized systems, compared with the Douglas bag method (P < 0.01). VO2 was an average of 0.018 l/min (or 18 ml/min) higher for the inspired system, compared with the Douglas bag method (P < 0.05). FEco2 was slightly lower (by an average of 0.0003 or 0.03%) for the expired system, compared with the Douglas bag method (P < 0.05). None of the other variables showed a significant difference between the computerized systems and the Douglas bag method. Significant interactions (power output × method) were found for VE, FEco2, and VC02 for the expired system (P < 0.05). However, because the magnitude of the interaction was small, post hoc tests were not carried out.

Figures 2 and 3 contain the Bland-Altman plots illustrating the individual difference scores (Douglas bag minus computerized system) for the inspiratory and expiratory methods. Overall, the difference scores (expressed as mean and 95% CI) were centered closely around zero, showing that both of the computerized systems agreed closely with the Douglas bag method.

Two of the subjects attained their maximum power output at 200 W. For the remaining six subjects, there were no statistical differences (at 250 W) among the Douglas bag method, inspired metabolic system, or expired metabolic system for any of the metabolic variables. Two other subjects could only complete 3 min of exercise at 250 W, so the collection period for their Douglas bag measurements for the final stage was over the second and third minute. Heart rate values achieved at the end of the test averaged 189 ± 16 beats/min (mean ± SD), and respiratory exchange ra-

<table>
<thead>
<tr>
<th>VO2, l/min</th>
<th>Douglas Bag</th>
<th>Expired</th>
<th>Inspired</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>9.1 ± 1.0</td>
<td>9.0 ± 0.9</td>
<td>9.3 ± 0.9</td>
</tr>
<tr>
<td>50 W</td>
<td>19.6 ± 1.7</td>
<td>19.2 ± 1.6</td>
<td>19.7 ± 1.6</td>
</tr>
<tr>
<td>100 W</td>
<td>29.6 ± 3.9</td>
<td>29.1 ± 3.7</td>
<td>29.6 ± 3.9</td>
</tr>
<tr>
<td>150 W</td>
<td>44.8 ± 8.5</td>
<td>44.5 ± 8.0</td>
<td>44.8 ± 8.3</td>
</tr>
<tr>
<td>200 W</td>
<td>70.5 ± 19.8</td>
<td>70.6 ± 19.7</td>
<td>70.8 ± 19.9</td>
</tr>
<tr>
<td>250 W</td>
<td>98.7 ± 18.4</td>
<td>98.6 ± 18.3</td>
<td>99.0 ± 19.3</td>
</tr>
</tbody>
</table>

**FEo2**

| Rest       | 0.1687 ± 0.0051 | 0.1685 ± 0.0050 | 0.1684 ± 0.0050 |
| 50 W       | 0.1586 ± 0.0050 | 0.1582 ± 0.0049 | 0.1582 ± 0.0049 |
| 100 W      | 0.1564 ± 0.0060 | 0.1557 ± 0.0060 | 0.1558 ± 0.0059 |
| 150 W      | 0.1585 ± 0.0080 | 0.1580 ± 0.0080 | 0.1580 ± 0.0077 |
| 200 W      | 0.1649 ± 0.0086 | 0.1645 ± 0.0088 | 0.1644 ± 0.0085 |
| 250 W      | 0.1718 ± 0.0069 | 0.1712 ± 0.0075 | 0.1714 ± 0.0074 |

**FCo2**

| Rest       | 0.0364 ± 0.0046 | 0.0361 ± 0.0045 | 0.0364 ± 0.0044 |
| 50 W       | 0.0442 ± 0.0027 | 0.0444 ± 0.0031 | 0.0442 ± 0.0029 |
| 100 W      | 0.0495 ± 0.0029 | 0.0501 ± 0.0048 | 0.0498 ± 0.0048 |
| 150 W      | 0.0503 ± 0.0067 | 0.0507 ± 0.0070 | 0.0504 ± 0.0069 |
| 200 W      | 0.0466 ± 0.0082 | 0.0469 ± 0.0083 | 0.0466 ± 0.0082 |
| 250 W      | 0.0419 ± 0.0077 | 0.0424 ± 0.0081 | 0.0422 ± 0.0078 |

**Values are means ± SD, reported as STPD; n = 8; at 250 W, n = 6. VE, minute ventilation; FEo2, fraction of O2 in expired gas; FCo2, fraction of CO2 in expired gas; VO2, O2 uptake; VC02, CO2 production; RER, respiratory exchange ratio.**
The main finding of the study was that the computerized system, whether configured to measure inspiratory or expiratory ventilation, yielded gas exchange variables that were extremely close to those obtained by the Douglas bag method. For power outputs ranging from 0 to 250 W, there were only small differences in $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$ or other variables. Even though some statistically significant differences were found, the differences were so small as to be not physiologically significant.

Because of the stability and linearity of recently developed O$_2$ and CO$_2$ gas analyzers, the major source of variation in assessing VO$_2$, VCO$_2$, VE or other variables. Even though some statistically significant differences were found, the differences were so small as to be not physiologically significant.

Regardless of whether ventilation is measured on the inspired or expired side, a “time lag” can occur when making a sudden transition between two power outputs. The increase in Vl or VE will be detected immediately, but the change in FEO$_2$ and FE$CO_2$ takes longer to be seen. This delay results from two components: 1) the time needed to wash out the mixing chamber, and 2) the time for the gas analyzers to detect the change in gas fractions within the mixing chamber. This temporal mismatch is less of a concern during
steady-state exercise when \( V_I \) and expired gas fractions are relatively stable but could be a factor during a graded exercise test.

Powers et al. (14) developed a method to correct for the time lag problem during nonsteady-state exercise by holding \( V_I \) data in memory for a user-specified time period (usually 15–20 s) before combining it with the \( F_{\text{EO}_2} \) or \( F_{\text{ECO}_2} \) values. The first component of the time delay varied with the ventilation rate. The second component of the delay was constant and reflected a 15-second time lag for the gas analyzers to read the gas concentrations in the mixing chamber. This second component predominates at higher flow rates, as the first component diminishes. The metabolic system (Rayfield Equipment, Waitsfield, VT) used by Powers et al. (14) had a plastic drying tube containing Drierite (W. A. Hammond Drierite, Xenia, OH) to dry the gas sample before it entered the gas analyzers, and this increased the time needed for stable gas fractions to be recorded.

The ParvoMedics software (inspired configuration) does not account for the delay between the measurements of ventilation rate and \( F_{\text{EO}_2} \) or \( F_{\text{ECO}_2} \), but this did not affect the system’s accuracy in measuring \( V_O_2 \). One reason is that, with the ParvoMedics system, the sample is transported from the mixing chamber to the gas analyzers by small-bore Nafion tubing (eliminating the need for a Drierite tube). Thus the response time of the gas analyzers in detecting changes in gas fractions within the mixing chamber is very short (~1 s). Furthermore, at moderate to high ventilation rates, the time needed to flush out the volume of the expired-gas hose and mixing chamber (combined total = 5.8 liters) is brief. In addition, a mismatch between \( V_I \) (or \( V_E \)) and gas fractions is minimized with the type of experimental protocol we used, which approximated a steady state during the last 2 min of each 5-min stage.

A major advantage to measuring \( V_E \) is that a single expired-gas hose connects the subject to the metabolic system (as opposed to two hoses for the alternative method). However, when ventilation is measured with a heated pneumotachometer, one must estimate the temperature of the gas as it moves through the screen. The averaging method is a simple method that satisfactorily describes the temperature of the exhaled gas. Another method is to place a temperature probe downstream of the heated pneumotachometer and directly measure the gas temperature. Kolkhorst et al. (8) used...
this method and found that expired temperatures 1 cm
downstream of the heated pneumotachometer were
stable at 30.2°C during 45 min of steady-state exercise.
This temperature was ~2.0°C higher than that mea-
sured with the heater turned off. In their study, the
probe temperature was equal to the average of room
temperature (23.5°C) and body temperature (37°C).

We also placed an LM35 precision temperature
probe (ParvoMedics, Salt Lake City, UT) in the mixing
chamber 1 cm above the downstream port of the pneu-
motachometer to measure expired air temperature.
However, this method of measuring expired gas tem-
perature resulted in \( \dot{V}E \) being overestimated by 2%.
Because the gas cools as it moves away from the heated
pneumotachometer, the mixing chamber temperature
would have underestimated the actual gas tempera-
ture inside the pneumotachometer. To express volumes
under STPD conditions, gas volumes must be corrected
to reflect a temperature of 0°C (273°Kelvin), \( P_B = 760 \)
mmHg, and no water vapor. This is done by multiply-
ing \( \dot{V}E \) ATPS by an STPD correction factor

\[
\text{STPD correction factor} = \frac{[273/(273 + T_a)] \times [P_B - P_{H_2O}] / 760 \text{ mmHg}}
\]

where \( T_a \) is the gas temperature at the point where
volume is measured (i.e., inside the pneumotachom-
er) and \( P_{H_2O} \) is the water vapor pressure of saturated
air (14). Because \( T_a \) was underestimated by the mixing
chamber temperature probe, this method inflated the
STPD correction factor, resulting in an overestimate of \( \dot{V}E \) STPD.

The average room temperature across all eight sub-
jects was 21.4°C. Thus the average temperature of the
expired gas was estimated to be 29.2°C (i.e., the aver-
age of 21.4 and 37°C). The mixing chamber values were
3–4° lower than those measured by the averaging
method. Thus the averaging method yielded ventila-
tion rates that were more closely matched with the
criterion method than did a mixing chamber tempera-
ture probe. It should be noted that a 1.0°C difference in
the estimated inspiratory temperature from the actual
temperature would result in only a 0.6% error in \( \dot{V}E \)
(see APPENDIX). Errors of this magnitude would have
only a minor effect on the calculation of \( \dot{VO}_2 \) consump-
tion.

The absolute accuracy of the computerized system
used in the present study was greater than observed
with some other metabolic systems (7, 11). For the
Aerosport KB1-C, the individual \( \dot{V}E \) error scores (Dou-
glas bag minus metabolic system) had a 95% CI of
approximately ±10 l/min (7). By comparison, the Parvo-
Medics system error scores (\( \dot{V}E \)) had a 95% CI range of
±1 l/min. Similarly, the ParvoMedics had one-sixth the
error in measuring \( FE_{O_2} \) and \( FE_{CO_2} \) compared with the
Aerosport KB1-C, indicating superior linearity and
stability of the gas analyzers or better gas sampling
techniques. Peel and Utsey (11) examined the Cosmed
K2 system and reported a systematic underestimation
of \( \dot{VO}_2 \) (by 12.5–17%) at all work rates. (It should be
noted that the Cosmed and Aerosport systems are
portable and thus may have unique design features that
do not allow for a fair comparison to the Parvo-
Medics system.) Porszasz et al. (12) examined the va-
lidity of the Medical Graphics CPX Express for minute
ventilation and reported a level of accuracy similar to
that seen with the ParvoMedics system. The Medical
Graphics system uses a symmetrically disposed Pitot
tube flow meter and adjusts for nonlinearity using
software correction. However, the Medical Graphics
system was not validated for metabolic variables such as
\( \dot{VO}_2 \) and \( \dot{VCO}_2 \) in this study.

Although many other computerized metabolic sys-
tems have been validated in the literature, several
studies used a previously validated metabolic system
as the criterion (10, 11, 18, 21). In studies in which the
Douglas bag method was used as the criterion, the gas
exchange measurements were either nonsimultaneous
(9, 16, 17) or nonsteady state (14), making direct com-
parisons with the present study difficult.

In conclusion, a computerized metabolic system
(ParvoMedics) using the Hans Rudolph 3813 pneumo-
tachometer to measure ventilation rates provides ac-
curate gas exchange measurements, irrespective of
whether \( \dot{V}I \) or \( \dot{V}E \) is measured. The method of averag-
ing body temperature and room air seems to be ade-
quate for estimating the temperature of the expired
gas moving through a heated pneumotachometer. Min-
imal errors in gas volumes result from this method,
suggesting that direct measurement of the gas temper-
ature is not necessary when measuring ventilatory
rates on the expired side. Furthermore, a computerized
metabolic system permits extremely precise measure-
ments to be made in a less time-consuming manner
than the Douglas bag technique.

APPENDIX

The effect of temperature on STPD conversion does not
only consist of the temperature-volume relationship described by
Charles’ law (1/303 = 0.33% per 1°C, at 30°C). It also consists
of a change in saturated water vapor pressure. At 30°C, the
saturated water vapor pressure is 31.5 mmHg. For any 1°C
change, the water vapor pressure changes by ~1.8 mmHg.
The dry \( P_d \) at 30°C = 760 – 31.5 = 728.5 mmHg. When the
temperature is around 30°C, the water vapor effect is 1.8/
728.5 per 1°C = 0.25%, which is also small. The combined
effect is ~0.6% per 1°C in expiratory flow temperature.

We thank Jason Langley and William O’Brien for assistance with
data collection and subject recruitment and Cary Springer of the
University of Tennessee Statistical Consulting Service for help with
the data analysis.

The authors have no financial interest in any of the products
mentioned in the text or in competing products.

REFERENCES

1. Armstrong LE and Costill DL. Variability of respiration and
metabolism: responses to submaximal cycling and running. Res

agreement between two methods of clinical measurement. Lan-

3. Cissik JH, Johnson RE, and Rokosch DK. Production of
gaseous nitrogen in human steady-state conditions. J Appl