Reliability and Validity of the Vmax\textsuperscript{ST} Portable Metabolic Analyzer

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Background: The reliability and validity of the SensorMedics Vmax\textsuperscript{ST} was tested. Methods: Thirty subjects (age = 24.5 ± 4.0 years, height = 174.8 ± 9.8 cm, weight = 70.3 ± 12.6 kg) performed treadmill exercise on three occasions, twice using the Vmax\textsuperscript{ST} and once using the SensorMedics 2900 system. Oxygen consumption (VO\textsubscript{2}; L/min) and heart rate (HR; beats/min) were measured continuously during three, 6- minute stages: 80 m/min, 0% grade; 94 m/min, 5% grade; and 160 m/min, 0% grade, and VO\textsubscript{2max}. Results: Reliability was high, and measurement error was low for VO\textsubscript{2} (R\textsubscript{xx} range = 0.97 - 0.99, CI = 0.94 - 1.00, SEM = 0.03 - 0.08 L/min) and HR (R\textsubscript{xx}=0.94-0.99,CI=0.88 - 1.00,SEM=1.8 - 3.2 beats/min). Validity was high for VO\textsubscript{2} (R\text{xy}range=0.92 - 0.98,CI=0.84 - 0.99,SEE=0.08 - 0.21 L/min) and HR (R\text{xy}=0.97 - 0.99,CI=0.94 - 1.00,SEE=0.9 - 1.8 beats/min). Mean differences in VO\textsubscript{2} between Vmax\textsuperscript{ST} and 2900 were small yet significant ($P<0.001$). Conclusions: The Vmax\textsuperscript{ST} demonstrated excellent reliability and validity for measuring VO\textsubscript{2} and HR over several exercise intensities. Small overestimates in VO\textsubscript{2} by the Vmax\textsuperscript{ST} are countered by low measurement error. 

Key Words: exercise measurement, oxygen consumption

Measurement of oxygen consumption (VO\textsubscript{2}) is performed to evaluate an individual’s cardiorespiratory fitness, or the energy cost of various physical activities. Cardiorespiratory fitness and physical activity are considered surrogate measures of health, where higher levels might indicate decreased risk for acute and chronic illnesses. Cardiorespiratory fitness measurements, via indirect calorimetry, are typically performed in a laboratory environment using open circuit spirometry via a metabolic cart. For obvious logistic reasons, the metabolic cart has limited function for measuring physical activity energy expenditure in field studies. A reliable and valid portable system to measure VO\textsubscript{2} in the field would allow direct measurement of oxygen consumption during sports or physical activities as well as occupational, leisure, and household tasks. In addition to obtaining VO\textsubscript{2} measures,
these portable devices could be used to validate additional indirect techniques such as motion sensors, heart rate (HR) monitors, and the estimated energy cost of specific activities (i.e., gardening) that are used in activity questionnaires. The validation of such devices is critical for public health research, as they are systematically used in large-scale epidemiological studies in an attempt to gain a better understanding of the health of a given community.

Over the past 25 years, several portable metabolic units have been developed and studied. These units include the Oxylog,\textsuperscript{2-3} the Cosmed K2\textsuperscript{4-5} and K4\textsuperscript{6}, the Aerospot KB1-C\textsuperscript{7} and TEEM 100,\textsuperscript{8,9} the CORTEX X1,\textsuperscript{10} and the MetaMax Cortex.\textsuperscript{11} In general, studies of these devices have been performed with small sample sizes (8–23 subjects) and results at various exercise intensities have been equivocal.

Recently, the Vmax\textsuperscript{ST} (SensorMedics, Yorba Linda, CA) portable metabolic unit was developed for use in laboratory and nonlaboratory settings. Prieur, Castells, and Denis\textsuperscript{12} performed a preliminary validation study of this system with 11 subjects. In their study, the validity of the Vmax\textsuperscript{ST} was compared against a gas exchange simulator and was evaluated during incremental human exercise. In the latter test, gases were collected simultaneously by both the Vmax\textsuperscript{ST} and Douglas bags. The Vmax\textsuperscript{ST} underestimated VO\textsubscript{2} when compared to the gas exchange simulator (–8%; range –12.6% and –3.4%) as well as during human exercise (–0.5%; range –14.3% and +13.3%). The authors contend that the traditional Douglas bag method is not completely satisfactory for comparison with a metabolic system because of ambient air contamination in the bag.\textsuperscript{12} Likewise, although the gas exchange simulator limits sources of error, it does not reproduce real human exercise conditions.

The design of our investigation overcomes both the limitation of simultaneous data collection\textsuperscript{4} as well as the possibility of ambient air contamination. To decrease the possibility of ambient air contamination, we used an alternate referee system than the Douglas bag. In addition, these tests were conducted separately in an attempt to overcome the difficulty of measurements made during the same exercise session. The validation portion of this study was not conducted utilizing a Douglas bag and the tests were performed separately. We were also interested in examining the reliability of this new portable device with a larger sample than used in previous studies. Therefore, our purpose was to test the reliability and validity of the Vmax\textsuperscript{ST} during steady state and maximal exercise.

**Methods**

**Subjects**

Thirty subjects (15 men, 15 women) from a university community participated in the study (age = 24.5 ± 4.0 years; height = 174.8 ± 9.8 cm; weight = 70.3 ± 12.6 kg). The study was approved by the university committee for research involving human subjects. Subjects gave written informed consent before entering the study. Each subject performed treadmill exercise on three occasions, at least 1 day apart, with time between tests not exceeding 2 weeks. The same protocol was performed on each visit. No incentives or financial support were provided by SensorMedics to conduct this study.
Instrumentation

Data were collected twice (for reliability analysis) using the SensorMedics VmaxST. In a third test, data were collected using the SensorMedics 2900 metabolic cart, which served as our criterion measure for respiratory gas exchange and metabolic measures. The SensorMedics 2900 metabolic cart has been previously validated at both submaximal and maximal exercise intensities (interclass correlation $r \geq 0.95$) against a referee system that included an Ametek S3A/1 oxygen analyzer, a Beckman LB-2 CO$_2$ analyzer, and an American Gas dry gas meter. The Polar Vantage XL monitor (Polar Electro, Inc., Gays Mills, WI) served as our criterion for HR measures.

Description of the VmaxST

The VmaxST is a cardiopulmonary stress test system for measuring pulmonary gas exchange under laboratory and field conditions. The unit operates on lithium batteries and weighs approximately 570 g. The VmaxST is composed of two housings (120 $\times$ 110 $\times$ 45 mm each) fastened to a shoulder harness and carried by the subject throughout exercise (Figure 1). The subject wears a small face mask and breathes through a volume transducer fixed to the mask. A gas sample line connects
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the volume transducer to the base unit on the subject’s shoulders. The VmaxST is a breath-by-breath system that measures volume continuously and determines CO₂ and O₂ concentrations simultaneously. It measures oxygen consumption via an open-circuit indirect calorimetry technique by assessing pulmonary gas exchange at the mouth. The components of the unit include an electrochemical O₂ analyzer, an infrared CO₂ analyzer, a digital turbine volume transducer, and thermistor temperature, silicon pressure, and HR sensors. Both HR and respiratory gases are transmitted via telemetry.

2900 Metabolic Measurement Cart

The SensorMedics 2900 metabolic cart also measures energy expenditure via open-circuit indirect calorimetry. It is a very popular unit that has been used in research and clinical settings for nearly 20 years and has been validated previously in laboratory environments. Subjects breathe through a one-way valve connected by a plastic hose to the metabolic cart. The 2900 metabolic cart can analyze pulmonary gases using either breath-by-breath or mixing chamber techniques. The cart components include a zirconium oxide O₂ analyzer, an infrared absorption CO₂ analyzer, and a mass flowmeter that measures thermal conductivity. Because we were interested primarily in exercise performed under steady-state conditions, the mixing chamber modality was utilized in this investigation.

Exercise Protocol

As stated previously, each subject completed three exercise tests. The order of tests was assigned randomly as either 2900-VmaxST-VmaxST or VmaxST-VmaxST-2900. This order was chosen to strengthen the reliability testing because the VmaxST trials were always performed consecutively. To ensure adequate analysis of the instrumentation, the subjects performed the same protocol during each testing session. All measurement devices were calibrated prior to each use.

Prior to exercise, respiratory gases and HR were collected continuously while subjects sat for 10 min. The purpose of the pre-exercise period was to insure that data collection began under similar conditions for all subjects. After the pre-exercise period, subjects performed a continuous exercise protocol on a motorized treadmill. Subjects walked at 80 m/min, 0% grade (6 min); walked at 94 m/min, 5% grade (6 min); and ran at 160 m/min, 0% grade (6 min). Immediately following the running stage, treadmill speed remained 160 m/min while the grade was increased 2.5% each minute until the subject reached volitional exhaustion. Subjects were considered to have attained VO₂max if they met two of the three criteria: a plateau in VO₂ (an increase in VO₂ not exceeding 2 ml · kg⁻¹ · min⁻¹ with increasing treadmill grade), respiratory exchange ratio (RER) > 1.0, or attainment of at least 90% age-predicted maximum HR (HRmax). The VmaxST measured HR continuously. Polar HR monitor measures were recorded every minute for comparison.

Statistical Analysis

Steady-state VO₂ (L/min) and HR were estimated by averaging the last 3 min of data collected during each exercise stage. The highest three consecutive 20-second
values were averaged to determine \( \text{VO}_{2\text{max}} \) (L/min). The highest HR obtained was considered \( \text{HR}_{\text{max}} \). Means (±SD) were computed for other variables of interest including treadmill time, min ventilation (\( V_e \)), RER, respiratory rate (RR), and fractional concentrations of inspired and expired gases (\( F_{I\text{O}_2}, F_{I\text{CO}_2}, F_{E\text{O}_2}, F_{E\text{CO}_2} \)).

Intraclass reliability (Rxx) of \( \text{VO}_2 \) and HR measures obtained from the VmaxST were estimated from repeated measures ANOVA. Single trial reliability was calculated using the Spearman-Brown Prophecy formula. Standard errors of measurement (SEM) and 95% confidence intervals (CI) were calculated for both \( \text{VO}_2 \) and HR.

Results of the two VmaxST tests were averaged and compared to results from the 2900 cart (\( \text{VO}_2 \)) and Polar Vantage XL (HR). Pearson product-moment correlations (Rxy) standard errors of the estimate (SEE), and 95% CI were calculated to estimate the validity of the VmaxST analyzer. Mean differences were compared by ANOVA. The method of Bland and Altman\(^{14}\) was used to graphically display the pairwise comparison of error results. This was done by plotting the difference between the 2900 metabolic cart and VmaxST \( \text{VO}_2 \) values for each subject against the mean value of the 2 methods. A priori significance level was set at \( P < 0.05 \).

Results
All subjects completed steady-state exercise and ran for at least one additional minute before reaching volitional exhaustion and \( \text{VO}_{2\text{max}} \). Average treadmill time was 23.3 ± 1.8 min and average \( \text{VO}_{2\text{max}} \) was 50.7 ± 7.1 mL · kg · min\(^{-1}\) and did not differ significantly by test or measurement method. Mean differences in \( \text{VO}_2 \) between the VmaxST and the 2900 cart were small, yet statistically significant (\( P < 0.001 \)), although mean differences in HR were not significant (Table 1). Table 2 shows that reliability of the VmaxST was high and SEM was low for both \( \text{VO}_2 \) (Rxx range = 0.97-0.99, CI range = 0.94-1.00, SEM range = 0.03-0.08 L/min) and HR (Rxx range = 0.94-0.99, CI range = 0.88-0.99, SEM range 1.8-3.2 b/min) across all exercise stages. Likewise, validity was high and SEE was low for both \( \text{VO}_2 \) (Rxy range = 0.92-0.97, CI range = 0.84-0.99, SEE range = 0.08-0.21 L/min) and HR (Rxy range = 0.97-0.99, CI range = 0.94-1.00, SEE range = 0.9-1.8 b/min) across all exercise stages (Table 3). Bland-Altman analysis indicated that the VmaxST overestimated \( \text{VO}_2 \) at all treadmill stages when compared to the 2900 metabolic cart (Figure 2). There were small, yet nonsignificant differences in mean \( V_e \), RER, and RR between instruments across all exercise stages (Table 4). \( F_{I\text{O}_2} \) and \( F_{E\text{O}_2} \) were significantly lower, although \( F_{I\text{CO}_2} \) and \( F_{E\text{CO}_2} \) were significantly higher when measured by the VmaxST compared to the 2900 (\( P < 0.001 \); Table 4).

Discussion
Our purpose was to test the reliability and validity of the SensorMedics VmaxST portable metabolic analyzer. Study participants were a convenience sample of motivated young adults with moderate to high levels of aerobic fitness, allowing for excellent internal validity. In addition, our sample size (\( N = 30 \)) is considerably larger than has been used in previous studies, which increases the credibility of our reliability and validity estimates.\(^{15}\) As can be seen in Table 2, both multiple and single trial reliabilities were extremely high, with very narrow confidence intervals.
Table 1  Mean (± SD) Values for Oxygen Consumption (VO₂) and Heart Rate (HR) Across All Stages for the 2900 Metabolic Cart and VmaxST (N = 30)

<table>
<thead>
<tr>
<th>Stage</th>
<th>VO₂ (L/min)</th>
<th>HR (beats/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2900</td>
<td>ST-1</td>
</tr>
<tr>
<td>W</td>
<td>0.89 ± 0.2</td>
<td>1.02 ± 0.2</td>
</tr>
<tr>
<td>%</td>
<td>1.42 ± 0.3</td>
<td>1.58 ± 0.3</td>
</tr>
<tr>
<td>R</td>
<td>2.34 ± 0.5</td>
<td>2.54 ± 0.5</td>
</tr>
<tr>
<td>M</td>
<td>3.45 ± 0.9</td>
<td>3.63 ± 1.0</td>
</tr>
</tbody>
</table>

Note: *P < 0.001; W = walking @ 80 m/min; % = walking @ 94 m/min and 5% grade; R = running @ 160 m/min and 0% grade; M = max (volitional exhaustion); ST = first trial on the VmaxST; ST-2 = second trial on the VmaxST; ST-X = mean of the 2 VmaxST trials; 2900 = metabolic cart

Table 2  Reliability of Oxygen Consumption (VO₂) and Heart Rate (HR) Measured on the VmaxST (N = 30)

<table>
<thead>
<tr>
<th>Stage</th>
<th>VO₂ (L/min)</th>
<th>HR (beats/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R&lt;sub&gt;xx&lt;/sub&gt; (CI)</td>
<td>Single (CI)</td>
</tr>
<tr>
<td>W</td>
<td>0.97 (0.94-0.99)</td>
<td>0.94 (0.88-0.97)</td>
</tr>
<tr>
<td>%</td>
<td>0.98 (0.96-0.99)</td>
<td>0.95 (0.90-0.98)</td>
</tr>
<tr>
<td>R</td>
<td>0.99 (0.98.0)</td>
<td>0.98 (0.96-0.99)</td>
</tr>
<tr>
<td>M</td>
<td>0.99 (0.98.0)</td>
<td>0.98 (0.96-0.99)</td>
</tr>
</tbody>
</table>

W = walking @ 80 m/min; % = walking @ 94 m/min and 5% grade; R = running @ 160 m/min and 0% grade; M = max (volitional exhaustion); R<sub>xx</sub> = reliability; (CI) = 95% confidence intervals; SEM = standard error of measurement for single trial; Single = single trial reliability
This indicates that not only were the day-to-day variations in VO$_2$ and HR response to exercise small and insignificant, but a single VmaxST trial can be used to obtain reliable results. The SEM values for VO$_2$ were low, with day-to-day measurement error averaging from 1-3%. The SEM for the VO$_2$ values was less than reported previously in our lab when testing the reliability of the 2900 metabolic cart used as the criterion measure in this study.$^{16}$ In addition, the measurement error was within biological variability as reported by Katch, Sady, and Freedson.$^{17}$

In addition, the VmaxST showed excellent validity when compared to the criterion measures (Table 3). The SEE values for VO$_2$ and HR ranged from 80-210 ml/min, and 1-2 b/min, respectively. Although the SSEE for VO$_2$ increased in m as subjects increased their exercise intensity, on a percentage basis, the error ml/min decreased from 14% to 6%.

Mean HR values measured via the VmaxST did not differ significantly from those measured via the Polar Vantage monitor. There was, however, a small, yet consistent and significant difference between VO$_2$ measured on the VmaxST compared to the 2900 metabolic cart. Specifically, the VmaxST overestimated VO$_2$ in nearly every instance (Figure 2). We examined $V_{\text{E}}$, RER, and RR and found they did not differ between instruments across exercise stages. We found, however, that $F_{1}\text{O}_2$ and $F_{E}\text{O}_2$ values were lower, while $F_{1}\text{CO}_2$ and $F_{E}\text{CO}_2$ values were higher.
on the VmaxST compared to the 2900 metabolic cart. This difference resulted in slightly higher VO$_2$ values measured by the VmaxST. The differences in fractional concentrations of O$_2$ and CO$_2$ could have been caused by a number of factors. First, the VmaxST recalculates F$_{I}$O$_2$ and F$_{I}$CO$_2$ on a breath-by-breath basis; the 2900 metabolic cart does not. Also, the face mask system used in the VmaxST might have resulted in slight rebreathing of expired gases, which would have affected the fractional concentrations of O$_2$ and CO$_2$. Despite these differences, however, the VO$_2$ over-prediction was small.

We observed minor behavioral differences in subjects during testing with the VmaxST. Use of the face mask allowed subjects to talk during low exertion exercise phases. Although subjects were discouraged from talking, it sometimes occurred. Subjects appeared to easily acclimate to the new apparatus and their respiratory patterns did not differ compared to when they used the traditional mouthpiece and nose clips on the 2900 metabolic cart. In addition, we observed that the adult small face mask was too large, and the pediatric large was too small for most female participants.

In summary, we found the SensorMedics VmaxST to be an extremely reliable and valid instrument for measuring cardiorespiratory variables during treadmill walking and running. Although the VmaxST consistently demonstrated a slight overestimate of VO$_2$, its measurement error was less than reported previously with the criterion 2900 metabolic cart. Future studies should focus on the utility of the VmaxST in field settings.

Acknowledgments

We would like to thank Adam Coughlin and Evelyn Warner for their technical assistance and the study participants for their cooperation during the investigation.
Table 4  Mean (± SD) Respiratory Values Across Stages for the 2900 Metabolic Cart and for the VmaxST (N = 30)

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th></th>
<th>%</th>
<th></th>
<th>R</th>
<th></th>
<th>M</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2900</td>
<td>ST-X</td>
<td>2900</td>
<td>ST-X</td>
<td>2900</td>
<td>ST-X</td>
<td>2900</td>
<td>ST-X</td>
</tr>
<tr>
<td>$V_{E}$ (L/min)</td>
<td>23.1 ± 4.4</td>
<td>22.7 ± 3.3</td>
<td>35.8 ± 5.8</td>
<td>35.8 ± 5.4</td>
<td>64.5 ± 12.1</td>
<td>62.3 ± 11.1</td>
<td>119.9 ± 32.0</td>
<td>114.8 ± 27.8</td>
</tr>
<tr>
<td>RER</td>
<td>0.85 ± 0.06</td>
<td>0.89 ± 0.05</td>
<td>0.90 ± 0.04</td>
<td>0.94 ± 0.04</td>
<td>0.96 ± 0.05</td>
<td>0.97 ± 0.05</td>
<td>1.22 ± 0.06</td>
<td>1.23 ± 0.07</td>
</tr>
<tr>
<td>RR (br/min)</td>
<td>25.4 ± 4.6</td>
<td>24.4 ± 4.7</td>
<td>26.6 ± 4.6</td>
<td>27.4 ± 5.1</td>
<td>37.4 ± 7.0</td>
<td>38.0 ± 6.7</td>
<td>49.9 ± 8.2</td>
<td>52.4 ± 8.6</td>
</tr>
<tr>
<td>$F_{I}O_{2}$</td>
<td>21.09 ± 0.02</td>
<td>20.80 ± 0.03$^a$</td>
<td>21.09 ± 0.02</td>
<td>20.78 ± 0.04$^a$</td>
<td>21.09 ± 0.02</td>
<td>20.88 ± 0.09$^a$</td>
<td>21.09 ± 0.02</td>
<td>20.89 ± 0.09$^a$</td>
</tr>
<tr>
<td>$F_{I}CO_{2}$</td>
<td>0.06 ± 0.01</td>
<td>0.19 ± 0.05$^a$</td>
<td>0.06 ± 0.01</td>
<td>0.18 ± 0.06$^a$</td>
<td>0.06 ± 0.01</td>
<td>0.20 ± 0.07$^a$</td>
<td>0.06 ± 0.01</td>
<td>0.24 ± 0.09$^a$</td>
</tr>
<tr>
<td>$F_{E}O_{2}$</td>
<td>16.67 ± 0.47</td>
<td>14.49 ± 0.42$^a$</td>
<td>16.45 ± 0.50</td>
<td>14.56 ± 0.45$^a$</td>
<td>16.79 ± 0.53</td>
<td>15.16 ± 0.60$^a$</td>
<td>17.38 ± 0.52</td>
<td>16.28 ± 0.51$^a$</td>
</tr>
<tr>
<td>$F_{E}CO_{2}$</td>
<td>3.92 ± 0.40</td>
<td>5.77 ± 0.34$^a$</td>
<td>4.35 ± 0.44</td>
<td>5.95 ± 0.41$^a$</td>
<td>4.23 ± 0.53</td>
<td>5.59 ± 0.50$^a$</td>
<td>4.93 ± 0.52</td>
<td>5.33 ± 0.61$^a$</td>
</tr>
</tbody>
</table>

Note: $^aP < 0.0001; V_{E} = \text{min ventilation}; F_{I}O_{2} = \text{fraction of inspired oxygen}; F_{I}CO_{2} = \text{fraction of inspired carbon dioxide}; F_{E}O_{2} = \text{fraction of expired oxygen}; F_{E}CO_{2} = \text{fraction of expired carbon dioxide}; RER = \text{respiratory exchange ratio}; RR = \text{respiratory rate}; W = \text{walking @ 80 m/min}; \% = \text{walking @ 94 m/min and 5\% grade}; R = \text{running @ 160 m/min and 0\% grade}; M = \text{max (volitional exhaustion)}; \text{ST-X = mean of the 2 VmaxST trials}; 2900 = \text{metabolic cart}
References