Assessment of Accuracy of the Vacu-Med 17053 Calibrator for Ventilation, Oxygen Uptake ($\dot{V}_{O_2}$), and Carbon Dioxide Production ($\dot{V}_{CO_2}$)

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BACKGROUND: Few have examined the accuracy of mechanical calibrators used to calibrate metabolic monitors. OBJECTIVE: To evaluate the Vacu-Med 17053 motorized syringe calibrator for accuracy against the accepted standard method: the Douglas bag. METHODS: We tested oxygen consumption ($\dot{V}_{O_2}$) values of 522–3,210 mL/min. We mixed room air and calibration gases in the pumping syringes of the Vacu-Med 17053 and evacuated those gases into a Douglas bag, measured the Douglas bag volumes and concentrations, and converted to pulmonary ventilation, $\dot{V}_{O_2}$, and carbon dioxide production ($\dot{V}_{CO_2}$). RESULTS: The Vacu-Med 17053 calibrator overestimated $\dot{V}_{O_2}$ by a mean 28.6 mL/min (1.3% error), underestimated $\dot{V}_{CO_2}$ by 6.9 mL/min (−1.7% error), and underestimated pulmonary ventilation by 0.98 L/min (−1.4% error). The $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ differences between the calibrator and the Douglas bag were larger at higher $\dot{V}_{O_2}$ levels. CONCLUSIONS: The $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ differences might be attributable to fluctuations of the calibrator settings. The Vacu-Med 17053 calibrator was accurate with the application of a mathematical correction. *Key words: calibration; oxygen consumption; carbon dioxide production; pulmonary ventilation; tidal volume; respiratory rate.* [Respir Care 2011;56(4):472–476. © 2011 Daedalus Enterprises]

Introduction

During the past 30 years, laboratories have switched from the cumbersome but accepted standard method (the Douglas bag) to automated systems to measure oxygen consumption ($\dot{V}_{O_2}$), carbon dioxide production ($\dot{V}_{CO_2}$), and pulmonary ventilation. However, questions remain regarding the accuracy and reliability of automated calibration systems because of differences in flow, volume, and gas concentration measurement methods.[1] The various instrumentation employed by each system causes different $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ values between systems.[2]

The diversity of available calibration systems necessitates an accepted standard method to calibrate metabolic monitors for accuracy and reliability. With the Douglas-bag method the clinician must either use calibration gas or obtain expiratory gas from humans and measure that gas with the metabolic monitor and the Douglas-bag method for volume and concentrations. The best technique to measure accuracy involves connecting the Douglas bag directly to the metabolic monitor's mixing chamber[3-6] and simultaneously measuring the gas with the metabolic monitor and the Douglas bag. However, some metabolic monitors do not allow for simultaneous collection, so a cumbersome but often used method is to switch from measurement by the metabolic monitor to collection in the Douglas bag during an exercise test.[7-11] In that method, the expired gas is not measured simultaneously by the meta-

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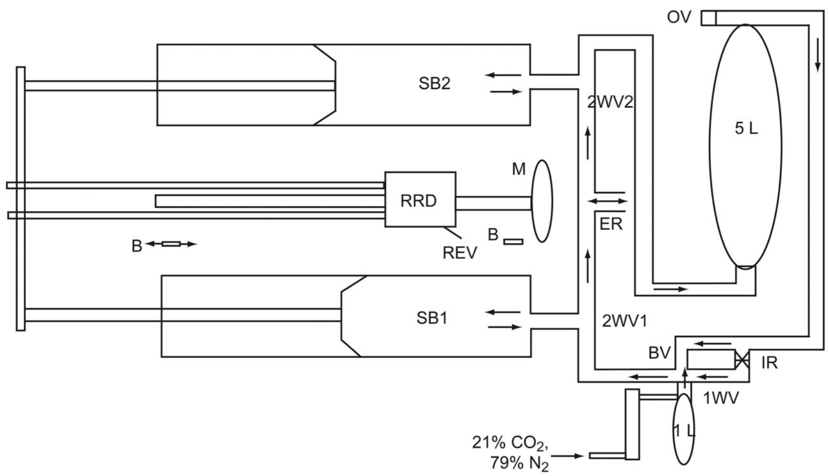

Fig. 1. Flow diagram of the Vacu-Med 17053 motorized syringe calibrator. SB1 = syringe barrel 1. SB2 = syringe barrel 2. B = bumpers. ER = expiratory restrictor. IR = inspiratory resistor (variable). M = motor. REV = reverser. RRD = rolling ring drive. 2WV = 2-way valve. 1WV = 1-way valve. BV = bypass valve. OV = overflow valve.

bolic monitor and the Douglas bag, so the measured volumes and concentrations are not directly comparable.

Several mechanical calibrators have been developed to overcome the limitations of the Douglas-bag method to calibrate a metabolic monitor. Some calibrators are accurate, but all have limitations, including delivery of calibration gas without correction for pulmonary air saturation, over-reliance on complex equations, and failing to prove accuracy of pulmonary ventilation in conjunction with $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$.[12-15] None of the available calibrators has been found to be as accurate or reliable as the Douglas-bag method. A recently released calibrator (model 17053, Vacu-Med, Ventura, California) was designed to work with various metabolic monitors, but the manufacturer has not provided accuracy and reliability data, nor has the 17053 been validated in independent academic research. In previous studies of mechanical calibrators, none of the instruments were validated for pulmonary ventilation, $\dot{V}_{O_2}$, and $\dot{V}_{CO_2}$ against the accepted standard method: Douglas bag.[12-15]

The 17053 calibrator's method differs from the Douglas-bag method in that it serves as the source of gas, and the clinician can calculate and alter pulmonary ventilation, $\dot{V}_{O_2}$, and $\dot{V}_{CO_2}$ output with the calibrator. We compared the 17053 calibrator to the Douglas-bag method.

Methods

This study was conducted in the Department of Kinesiology at the University of Kentucky, Lexington, Kentucky. Vacu-Med was not involved in designing the study, data collection, analysis, interpretation, or preparing the manuscript.

Calibrator Set-up and Operation

The 17053 calibrator was designed to calibrate and evaluate the accuracy of automated metabolic monitors of all types. The 17053 digitally displays tidal volume (V_T) in L, respiratory frequency in breaths/min, and flow in L/min. The 17053 has two 4.0-L syringes that draw in room air and calibration gas. Figure 1 shows a schematic of the 17053 calibrator, with arrows indicating the direction of air flow. Two actions occur simultaneously during inspiration: room air flows into syringe barrel 2 through a 2-way valve, and syringe barrel 1 fills with room air from the 5.0-L storage bag and calibration gas (which, ideally, is 21% CO_2 and 79% N_2) from the 1.0-L storage bag. The 2 gases flowing into syringe barrel 1 mix together at the bypass valve and the inspiratory restrictor, and enter syringe barrel 1 through 2-way valve 1.

During expiration there are also 2 simultaneous events: room air from syringe barrel 2 flows back through 2-way valve 2, into the 5.0-L reservoir bag; and air from syringe barrel 1 flows through the 2-way valve 1 past the expiratory restrictor and out of the calibrator into a metabolic monitor or a Douglas bag for measurement. If the 5.0-L bag becomes full, excess room air empties through the overflow valve. The respiratory cycle is controlled by the motor and rolling ring drive. The 17053 calibrator can be adjusted for respiratory frequency and V_T. The flow of calibration gas is controlled by a rotometer, next to the 1.0-L reservoir bag.

Evaluation of Calibrator Accuracy

We created a standard protocol (Table 1) to study a wide physiological range of $\dot{V}_{O_2}$ (512–3,150 mL/min), $\dot{V}_{CO_2}$

Table 1. Sample Calibration Protocol*

V_T (L)	Respiratory Rate (breaths/min)	Rotometer Setting	Gas Flow (L/min)	Expected $\dot{V}_{O_2}$ at STPD (mL/min)	Expected $\dot{V}_{CO_2}$ at STPD (mL/min)
1.0	8–10	20	2.73	512	522
1.0	12–15	20	2.73	512	522
1.0	17–20	20	2.73	512	522
2.0	15–20	40	5.27	989	1,007
2.0	25–30	40	5.27	989	1,007
2.0	35–40	40	5.27	989	1,007
2.0	15–20	60	7.43	1,394	1,420
2.0	25–30	60	7.43	1,394	1,420
2.0	35–40	60	7.43	1,394	1,420
2.0	15–20	80	9.42	1,767	1,800
2.0	25–30	80	9.42	1,767	1,800
2.0	35–40	80	9.42	1,767	1,800
3.0	25–30	100	11.60	2,176	2,217
3.0	35–40	100	11.60	2,176	2,217
3.0	45–50	100	11.60	2,176	2,217
3.0	25–30	120	13.67	2,564	2,612
3.0	35–40	120	13.67	2,564	2,612
3.0	45–50	120	13.67	2,564	2,612
3.0	25–30	140	15.75	3,151	3,210
3.0	35–40	140	15.75	3,151	3,210
3.0	45–50	140	15.75	3,151	3,210

* The expected oxygen consumption ($\dot{V}_{O2}$) and carbon dioxide production ($\dot{V}_{CO2}$) were calculated by the O_2Cal software (Vacu-Med, Ventura, California), based on the room conditions (barometric pressure 760 mm Hg, relative humidity 58%, and ambient temperature 23°C).
V_T = tidal volume
STPD = standard temperature and pressure, dry

(522–3,210 mL/min), and pulmonary ventilation (8–122 L/min), with 3 V_T and frequency settings, and 7 rotometer settings to control the calibration gas. As suggested by the manufacturer, to obtain realistic and accurate values, the rotometer was never set below 20 or above 140. At each setting, mixed gas from the calibrator was collected in the Douglas bag for one minute, beginning with expiration and ending with inspiration. Gas concentrations were analyzed with a paramagnetic O_2 analyzer and an infrared CO_2 analyzer (AEI Technologies, Quogue, New York). The gas was then emptied from the Douglas bag by a vacuum (Shop-Vac, Williamsport, Pennsylvania) that pulled the air from the bag through a Rayfield meter (Rayfield Equipment, Whitsfield, Vermont) at 2.5 L/s. Both the Rayfield meter and Douglas-bag method were previously evaluated to ensure proper assessment of the mechanical calibrator (pulmonary ventilation error 0.09%, $\dot{V}_{O_2}$ error 0.08% after the $\dot{V}_{O_2}$ correction equation).

We conducted the protocol in its entirety 7 times, and entered the data into the software that accompanies the 17053 calibrator (O2Cal.xls, Vacu-Med, Ventura, California) and predicts the $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ values based on information entered by the investigator, including room temperature, barometric pressure, relative humidity, and calibration gas flow.

Data Analysis

With statistics software (SPSS 16.0, SPSS, Chicago, Illinois) we analyzed the differences between the measured (via Douglas bag) and predicted (by Vacu-Med) pulmonary ventilation, $\dot{V}_{O_2}$, and $\dot{V}_{CO_2}$ values, with a one-sample Student *t* test. Statistical significance was set at $\alpha = .05$. We used linear regression to further assess potential sources of error, and created Bland-Altman plots to evaluate trends and outliers.

Results

Table 2 shows the mean pulmonary ventilation, $\dot{V}_{O_2}$, and $\dot{V}_{CO_2}$ differences and the *P* values for those differences. The mean difference in pulmonary ventilation was -0.98 ± 1.78 L/min ($P < .001$), representing a −1.4% error. There was close agreement between the Douglas bag and Vacu-Med 17053 values for ventilations less than 60 L/min. However, between 85 and 120 L/min the difference increased to approximately 5–10 L/min. Overall, there was a 2.4% error at the higher pulmonary-ventilation values, compared to a −1.0% error at the lower pulmonary-ventilation values. The mean $\dot{V}_{O_2}$ difference was 28.6 ± 75.2 mL/min ($P < .001$), indicating a 1.3% error. The mean $\dot{V}_{CO_2}$ values differed by -6.9 ± 60.9 mL/min ($P = .17$) between the Douglas-bag and 17053 calibrator, signifying a −1.7% error. Linear regression analyses showed that respiratory rate ($P = .048$) and V_T ($P = .008$) were the source of error for pulmonary ventilation, whereas respiratory rate impact was the source of error for $\dot{V}_{O_2}$ ($P < .001$) and $\dot{V}_{CO_2}$ ($P = .02$). Essentially, the respiratory rate impacted the error in pulmonary ventilation, $\dot{V}_{O_2}$, and $\dot{V}_{CO_2}$.

Figure 2 shows the Bland-Altman plot of the Douglas-bag values versus the Vacu-Med-17053-minus-Douglas-bag values. At $\dot{V}_{O_2}$ 500 mL/min the difference between the Douglas-bag and Vacu-Med 17053 values was close to zero, but at values above 500 mL/min the difference averaged 36.3 mL/min. Thus, as $\dot{V}_{O_2}$ increased, calibrator error increased. The 17053's mean $\dot{V}_{CO_2}$ was 6.9 mL/min greater than that of the Douglas bag ($P = .17$).

Discussion

Our major finding is that the Vacu-Med 17053 calibrator overestimated $\dot{V}_{O_2}$ by 1.3%, and that error increased as $\dot{V}_{O_2}$ increased, and it underestimated $\dot{V}_{CO_2}$ by −1.7%. Ideally, the $\dot{V}_{O_2}$ difference should match the $\dot{V}_{CO_2}$ difference, since the Vacu-Med 17053 was designed to produce a respiratory exchange ratio of 1.0, but that was not the case.

Table 2. Differences in Pulmonary Ventilation, $\dot{V}_{O_2}$, and $\dot{V}_{CO_2}$, and *P* Values for Those Differences

		P			
	Mean ± SD	*t* Test	V_T*	Ball Float*	Frequency*
Pulmonary ventilation difference (L/min)	–0.98 ± 1.78	< .001	.008	.21	.048
$\dot{V}_{O_2}$ difference (mL/min)	28.6 ± 75.2	< .001	.89	.82	< .001
$\dot{V}_{CO_2}$ difference (mL/min)	–6.9 ± 60.9	.17	.73	.55	.02

* Calculated via linear regression.
$\dot{V}_{O_2}$ = oxygen consumption
$\dot{V}_{CO_2}$ = carbon dioxide production
V_T = tidal volume

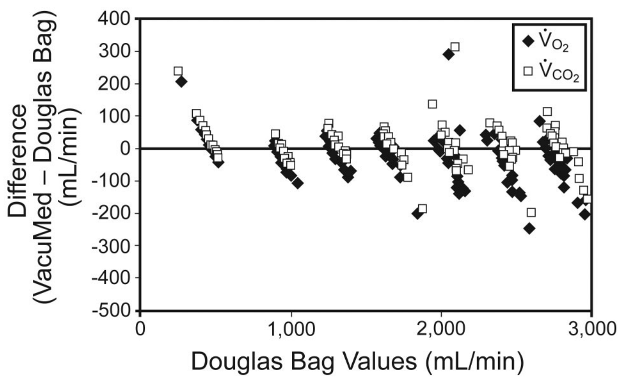

Fig. 2. Bland-Altman plot of oxygen uptake ($\dot{V}_{O_2}$) and carbon dioxide production ($\dot{V}_{CO_2}$) values measured with a Douglas bag versus with the Vacu-Med 17053 motorized syringe calibrator.

There was a trend of increasing $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ variability with rising pulmonary ventilation. This may have been caused by the pumping of the rolling ring drive, which forcefully moves air through the calibrator, which shakes the calibrator and thereby might cause fluctuations in the volume of calibration gas entering the calibrator. The calibrator was secured to a hard surface, and pressure from the gas tank was adjusted to minimize the shaking, but some fluctuation was unavoidable. In addition, the calibrator uses tubing that creates dead space within the device, which also may have contributed to differences between the calibrator and the Douglas-bag method. We measured the tubing dead space by filling the connectors and tubing with water and measuring the volume with a graduated cylinder, and the dead-space volume was 260 mL. The dead space may have contributed to calibrator error because upon expiration air remains in the tubing rather than moving into the Douglas bag, and that air then mixes with the air in the following inspiration.

The Vacu-Med 17053 calibrator underestimated pulmonary ventilation by −1.4%, and we attribute that error to V_T and respiratory rate. As with $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$, the error was greater at the higher pulmonary ventilation levels (−2.4%) than at the lower pulmonary-ventilation levels (−1.0%), so the forceful movement of the rolling ring drive and shaking of the calibrator at the higher frequencies may have altered the air volume flowing into the calibrator.

Limitations

While our protocol covers a realistic physiological range of pulmonary ventilation, $\dot{V}_{O_2}$, and $\dot{V}_{CO_2}$ in an average human, the values are not as high as those in a highly trained athlete, in whom $\dot{V}_{O_2}$ may exceed 5,000 mL/min. Such values cannot be produced by the Vacu-Med 17053 calibrator because the manufacturer limited the rotometer scale to 140, which allows calibration gas into the system via the 1.0-L balloon at 15.75 mL/min.[16] Despite this inability to match athletic $\dot{V}_{O_2}$ values, 3,151 mL/min is above the maximum values obtained by average humans and is acceptable for evaluating metabolic monitors.

Conclusions

The Vacu-Med 17053 calibrator exhibited small errors versus the Douglas-bag method for pulmonary ventilation (−1.4% error), $\dot{V}_{O_2}$ (1.3% error), and $\dot{V}_{CO_2}$ (−1.7% error) across resting and exercising levels. However, the Vacu-Med 17053 exhibited larger errors at higher breathing frequencies, and the highest available $\dot{V}_{O_2}$ calibration value is 3,151 mL/min, which is not as high as needed for assessing elite athletes. Therefore, the Vacu-Med 17053 may be useful to test the accuracy and validity of a metabolic monitor, but is limited at very high exercise values.

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