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TECHNICAL NOTE

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Validity of a new portable indirect calorimeter: the AeroSport TEEM 100

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Abstract The purpose of this study was to compare oxygen uptake ($\dot{V}O_2$) values collected with a new portable indirect calorimeter (AeroSport TEEM 100 Metabolic Analysis System) against a more traditional large calorimeter system that has been reported to be valid and reliable (SensorMedics 2900 Metabolic Measurement Cart). Minute ventilations ranging from rest up to heavy exercise were compared with simultaneous measurements from a 120-l Tissot gasometer. Each of the three TEEM 100 pneumotachs were tested. Three hundred and sixty-one separate ventilation tests were performed using the low-flow, medium-flow, and high-flow heads of the portable calorimeter. For each of the pneumotachs, the correlation between the portable calorimeter values and the gasometer values exceeded $r=0.94$. The standard error of estimate for the low-, medium- and high-flow pneumotach were 5.96, 4.89 and 9.0%, respectively, expressed relative to the mean gasometer value. Simultaneous measurements of $\dot{V}O_2$ using the portable calorimeter and the SensorMedics 2900 unit were compared during rest and at work rates starting at zero watts, increasing by 25 W to 150 W. Each work rate was of 4 min duration. The average of data from minutes 3 and 4 were used in all analyses. There was very close agreement between the two metabolic measurement systems. Except at the 100-W work rate, where the $\dot{V}O_2$ difference was small (3.9%), yet statistically significant, all of the other differences in $\dot{V}O_2$ were small and non-significant. The scatter plot of $\dot{V}O_2$ for the SensorMedics versus the portable AeroSport calorimeter revealed close agreement; the correlation was $r=0.96$, (SEE=3.95%). It was concluded that the AeroSport TEEM 100 portable calorimeter system produces valid data at rest and at low to moderate work rates compared to a criterion, large system.

Key words Oxygen uptake · Indirect calorimetry · Portable analysis · Exercise · Metabolism

Introduction

Attempts to build a valid reliable, indirect calorimeter have their genesis in the pioneering work of the French chemist Antoine Lavoisier (Lavoisier and de la Place 1789). Subsequent improvements in indirect calorimetry represented by such devices as the Haldane respirometer (Haldane 1892), and the Atwater and Rosa (1899) calorimeter have eventually resulted in numerous technological breakthroughs in automated measurement techniques (McNeill et al. 1987; Norton 1980; Webb and Troutman 1970; Wilmore and Costill 1974; Wilmore et al. 1976). Most of the calorimeters in use today constitute a major leap forward in technology, making it possible to measure human metabolism in different environments and locations with relative ease (Kleiber 1975).

The next technological breakthrough in calorimetry would be the development of a portable indirect calorimeter, since even the smallest of the current systems cannot be used away from the laboratory because of size, weight, and dependence on AC/DC electrical operations. To be useful, a portable indirect calorimeter must be light enough to be easily transportable, as well as battery operated. Analyses must be rapid, and integration with a high-speed microprocessor essential. To date, there is only one system (Cosmed K-2 System)

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commercially available that meets these specifications (Lothian et al. 1993; McNeill et al. 1987; Peel and Utsey 1993), and it does not include measurements of carbon dioxide; hence it uses an assumed respiratory exchange ratio (*R*) value in the calculations of energy expenditure.

In the present report we present the results of our validation testing of the newest portable indirect calorimeter measurement system commercially available, the TEEM 100 Total Metabolic Analysis System (AeroSport, Ann Arbor, Mich.).

Description of the portable indirect calorimeter

The system (Fig. 1) measures 25.4×25.4×8.9 cm, weighs about 3.3 kg and comes with a fully integrated 12-V rechargeable battery that can be operated for up to 2 h per charge (120 min of continuous data collection).

The unit uses a unique variation of the classic principles of open-circuit spirometric analysis (Consolazio et al. 1963). Briefly, as respiratory gas is exhaled through the pneumotach, a micro-sample proportional to the expired flow is drawn from the sample-in port of the lightweight pneumotach, into the base unit. A fixed rate of this proportional sample is drawn into a micro-mixing chamber (10 cc) for volumetric integration of flow. Following gas analysis and flow integration, the gas is exported out the back of the system to ambient air. The whole system is under microprocessor control. Oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and *R* are calculated according to standard procedures (Consolazio et al. 1963; McArdle et al. 1991). Data output are presented at a 20-s intervals on a four-line LED. Additionally, the data can be stored in non-volatile memory (remains in memory even when the unit is turned off) and can be download to any RS-232 parallel device. The unit prints out $\dot{V}O_2$, $\dot{V}CO_2$, *R*, minute ventilation at standard ($\dot{V}_{E_{STPD}}$) and body ($\dot{V}_{E_{BTPS}}$) temperature and pressure, O_2%, CO_2%, true O_2, $O_2 \cdot kg^{-1}$ body mass, and time on a 20, 40, or 60-s basis. Moreover, the unit has a built-in receiver for use with a heart rate monitor.

Ventilation volume is measured with a flat-plate orifice pneumotach. The orifice is so constructed as to give a maximum pressure drop of 0.0508 m of water at peak flow. A silicon wafer, bonded string gauge pressure transducer is used to measure the differential pressure instantaneously, when it is connected to pressure ports located on both sides of the orifice plate.

The oxygen sensor is a galvanic fuel cell. At 0% O_2 there is no current, and no output. The output is essentially linear and with a line of identity drawn through zero and 20.93%. The effect of CO_2, present in the expired air during analysis, tends to enhance the output signal (1% CO_2 increases the O_2 signal by 0.3%), resulting in less than a 0.05% absolute O_2 error when the proportions of O_2 and CO_2 total 20 to 21%, as occurs during normal metabolic studies. CO_2 is measured by the principle of non-dispersive infrared analysis. Ambient air is used to zero the CO_2 sensor output.

Fig. 1 The AeroSport TEEM 100 Total Energy Expenditure Measurement system

A unique aspect of the portable indirect calorimeter is "proportional sampling" and "electronic variable sampling" (EVS). Proportional sampling works on the basis that for each defined unit of volume that passes through the pneumotach, a microsample of flow, proportional to the total flow, is admitted to the unit via a high-frequency sampling valve. This valve is regulated at subatmospheric pressure. When the valve opens for a fixed period of time, a portion of sample gas is allowed to enter the sampling system. The volume of each sample is very small, and the net result is a mixture of expired gas of only a few milliliters per breath that is absolutely representative of the total flow going through the pneumotach.

Methods

Data were collected at two sites: the Applied Physiology Laboratory at the University of Michigan, and the Exercise Physiology Laboratory at Cornell University Medical College (N.Y.). All ventilation testing was done at the Michigan site, while $\dot{V}O_2$ validation was done at both sites, using identical protocols and procedures.

Ventilation volumes

Ventilation volumes measured by the portable indirect calorimeter unit were compared with volumes simultaneously collected in a 120-l Tissot gasometer. The portable indirect calorimeter uses three different pneumotachs, depending on ventilation range. According to the manufacturer (AeroSport 1993), the low-flow pneumotach operates at a $\dot{V}_{E(BTPS)}$ range between 2 and 30 $l \cdot min^{-1}$, the medium-flow pneumotach operates at a $\dot{V}_{E(BTPS)}$ range between 10 and 120 $l \cdot min^{-1}$ and the high-flow pneumotach operates with a $\dot{V}_{E(BTPS)}$ range between 50 and 200 $l \cdot min^{-1}$. We tested each pneumotach under the same operating procedures and environmental conditions.

Table 1 Ventilation data for the TEEM 100 and the Tissot gasometer

	Low flow		Medium flow		High flow	
	TEEM 100	Gasometer	TEEM 100	Gasometer	TEEM 100	Gasometer
Mean	14.62	14.47	37.87	36.43	58.83	59.53
SD	8.3	8.5	28.4	26.1	22.9	22.3
Mean difference	−0.141		−1.441		0.702	
Degrees of freedom ($n-1$)	147		144		67	
t-ratio	−1.927		−5.773		1.059	
P-value	0.056		0.0001		0.293	

The output from the pneumotach was placed in-line with two-way non-rebreathing valve (Hans Rudolph type). The output from the non-rebreathing valve was fed into the gasometer via 1 m of corrugated tubing. Each pneumotach was tested while subjects rested on or pedaled a friction-type bicycle ergometer. All gases were collected on a minute-by-minute basis. The gases were allowed to equilibrate in the gasometer to reach temperature equilibration, prior to recording.

Of the 361 separate tests, 68 were performed on the high-flow pneumotach, 145 on the medium-flow pneumotach. All ventilation volumes are reported as STPD. Ten college-age subjects, five women [mean (SD) age, 18.6 (2.1) years; body mass, 54 (5) kg] and five men [age, 19.4 (2.2) years; body mass, 71 (6) kg] participated in these studies. All subjects gave written informed consent, following a verbal and written explanation of all testing procedures.

Comparisons between the portable indirect calorimeter and the gasometer values were made using a paired t-test, and simple linear regression analysis. Significance was established at $P \leq 0.05$.

Oxygen uptake

$\dot{V}O_2$ data from the portable indirect calorimeter were compared against data simultaneously collected using a SensorMedics 2900 Metabolic Measurement Cart (SM-MMC) as the criterion. Subjects breathed directly into the portable calorimeter pneumotach. A two-way non-rebreathing valve was placed in the output port of the portable calorimeter that fed directly into the input hose of the SM-MMC.

The testing protocol consisted of a bicycle ergometer step-increment test, starting at rest, then progressing to unloaded cycling (0 W, unloaded cycling at 60 rpm), and increasing by 25 W thereafter, to 150 W. Each work rate was 4 min duration. Data collection with the portable indirect calorimeter and SM-MMC was initiated at minutes 3 and 4, with minutes 1 and 2 serving as an equilibration phase. The minute 3 and 4 data were averaged to represent the steady-rate $\dot{V}O_2$ for each work rate.

All subjects were familiarized with data collection procedures prior to testing. Resting metabolic measurements were initiated after subjects had rested for at least 5 min. By placing both units in-line, it was possible to obtain true simultaneous measurements. Both units were calibrated prior to each test following each manufacturer's detailed instructions, using gases analyzed with the MicroScholander apparatus (Scholander 1947).

Comparisons between the portable indirect calorimeter and the SM-MMC were made with a paired t-test and simple linear regression analysis.

A total of 21 subjects participated in the $\dot{V}O_2$ studies. There were 12 women [age, 19.4 (3.5) years; body mass, 56.3 (4.6) kg] and 9 men [age, 22 (1.7) years; body mass, 71.4 (5.0) kg]. All subjects were sedentary and not participating in regular physical activity. As in the ventilation studies, subjects gave written informed consent prior to participation.

Validity and reliability of the SM-MMC has been previously established (Kane et al. 1983; Kannagi et al. 1983; Wilmore et al. 1976).

Results

Table 1 presents the ventilation data for the portable indirect calorimeter and the gasometer. There are small mean differences between the portable indirect calorimeter pneumotachs and the gasometer values at the low, medium, and high flow rates. The significant mean difference for the medium-flow pneumotach is a reflection of the large number of subjects, and the large range of values, and hence the large SD.

Figures 2–4 present the regressions of the portable indirect calorimeter ventilations versus gasometer ventilation values. In each case, the slopes of the regression are very close to, and not significantly different than 1.0. Note that the graphs are drawn to show the lines of identity, and not the regression lines. This was done to illustrate the closeness of fit to the absolute criterion, and not necessarily to depict the bivariate relationship, which is given by the listed equations, correlations and standard error of estimate (SEE) values.

Table 2 presents the means, SD, t-ratios and P-values for the $\dot{V}O_2$ data. Note the differences in the number of subjects completing each work rate.

Except at 100 W there were no significant differences between the mean $\dot{V}O_2$ values for the portable calorimeter versus the SM-MMC. At 100 W, the mean difference is only 76 ml, (3.9% difference). While statistically significant at the $P=0.03$ level, the magnitude of

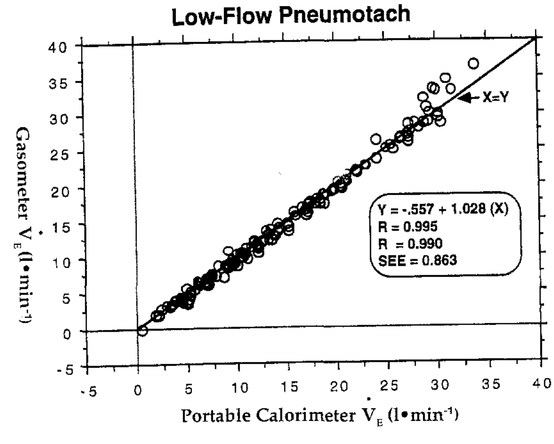


Fig. 2 Regression of portable calorimeter versus gasometer ventilation values for the low-flow pneumotach, based on 148 values

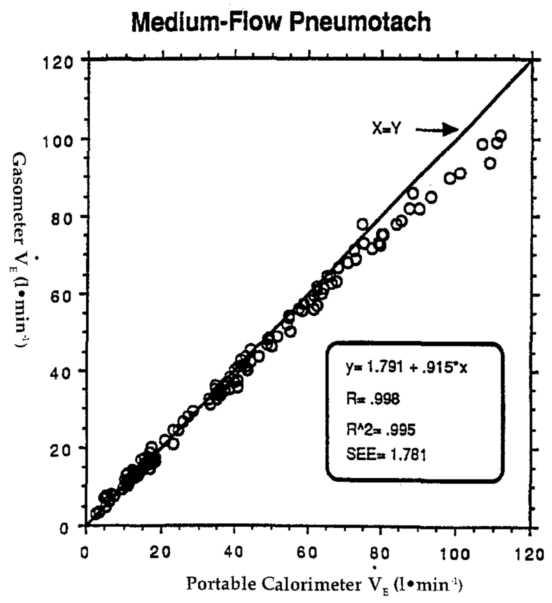


Fig. 3 Regression of portable calorimeter versus gasometer ventilation values for the medium-flow pneumotach, based on 145 values

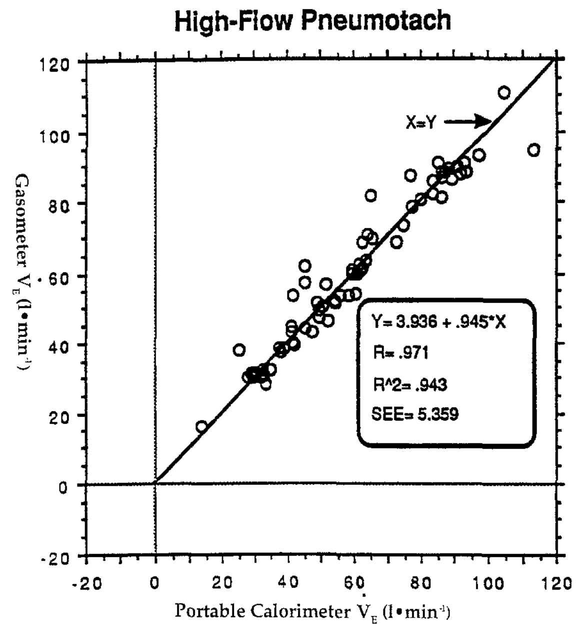


Fig. 4 Regression of portable calorimeter versus gasometer ventilation values for the high-flow pneumotach, based on 68 values

the difference is quite small, and of no practical importance. All of the other mean differences, expressed as a percentage of the mean SM-MMC value, are under 4%, except at 125 W where the difference is 6.6%.

Figure 5 shows a combined plot of $\dot{V}O_2$ for the SM-MMC (y axis), versus $\dot{V}O_2$ for the portable calorimeter (x axis). The line of identity is also displayed. For these combined data the correlation is $r=0.97$, and the SEE is ±3.95%, expressed as a percentage of the mean SM-MMC value. As can be observed, there appears a tendency for the portable calorimeter values to underestimate the criterion values at the higher values. This tendency is small, however.

Figure 6A and B shows the portable calorimeter $\dot{V}O_2$ plotted against the SM-MMC $\dot{V}O_2$ at 25 and 100 W. The regression equations are also presented. The separate regressions for the other work rates are nearly the same as these examples, and serve to illustrate the high validity of the portable calorimeter at the individual work rates. The average correlation is $r=0.92$, and the SEE is 4.2% of the mean SM-MMC value.

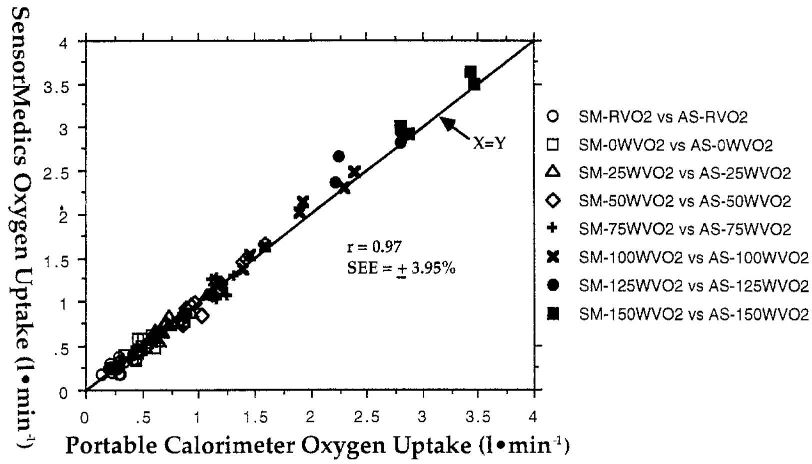
Discussion

Since the $\dot{V}O_2$ data collection was done simultaneously and in-line, we are confident that comparisons between the two systems are empirically justified. We were initially concerned that since the portable calorimeter pneumotach was placed within 15 cm proximal to the mouth, and the SM-MMC analyzing unit was located about 1.5 m downstream (length of hose from the mouthpiece to the SM-MMC unit), that we would experience significant time off-sets between the two units. The fact that there are small and non-significant differences in $\dot{V}O_2$ at different work rates between the units suggests that this was not the case. The SM-MMC unit adequately adjusts for the time delay from the mouth

Table 2 Oxygen uptake ($\dot{V}O_2$) data for the portable calorimeter and the SensorMedics 2900. The data represent the average of minutes 3 and 4 at each work rate. The medium-flow pneumotach was used for all testing

Work rate	SensorMedics $\dot{V}O_2$ (l·min^{-1})		Portable calorimeter $\dot{V}O_2$ (l·min^{-1})					
	Mean	SD	Mean	SD	n	Mean difference	t-Ratio	P-value
Rest	0.277	0.063	0.281	0.73	21	0.004	−0.301	0.7646
0 W	0.533	0.124	0.546	0.137	16	0.013	−0.771	0.4527
25 W	0.749	0.229	0.744	0.211	19	−0.005	0.383	0.7062
50 W	1.082	0.294	1.095	0.251	13	0.013	−0.637	0.5363
75 W	1.168	0.120	1.189	0.81	6	0.021	−0.406	0.7015
100 W	1.928	0.415	1.852	0.394	7	−0.076	2.668	0.0371
125 W	2.702	0.248	2.523	0.332	4	−0.179	2.119	0.1243
150 W	3.270	0.348	3.143	0.351	4	−0.127	2.514	0.0867

Fig. 5 Combined plot of oxygen uptake ($\dot{V}O_2$) for the SensorMedics (y axis) versus $\dot{V}O_2$ uptake for the portable calorimeter (x axis). The line of identity is also displayed. The legend should be read as follows: SM-R $\dot{V}O_2$ vs AS-R $\dot{V}O_2$ = SensorMedics resting $\dot{V}O_2$ versus portable calorimeter Resting $\dot{V}O_2$; SM-0 W $\dot{V}O_2$ vs AS-0 W $\dot{V}O_2$ = SensorMedics Zero W $\dot{V}O_2$ versus portable calorimeter Zero W $\dot{V}O_2$; SM-25 W $\dot{V}O_2$ vs AS-25 W $\dot{V}O_2$ = SensorMedics 25 W $\dot{V}O_2$ versus portable calorimeter 25 W $\dot{V}O_2$; and so on for the 50, 75, 100, 125 and 150 W workrate



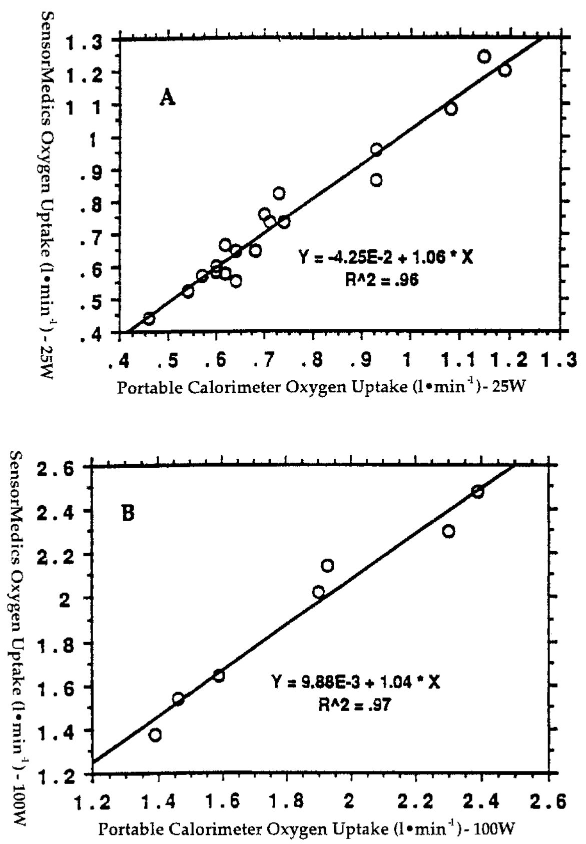


Fig. 6 Portable calorimeter oxygen uptake plotted against the SensorMedics 2900 oxygen uptakes at the 25 W (a) and 100 W (b) work rates. The regression equations are also presented

to the analyzing unit, as described in the manual (SensorMedics 1991).

The independent ventilation comparisons between the portable calorimeter pneumotachs and gasometer revealed the pneumotachs to be very consistent and valid. As can be observed in Fig. 2, the closeness of fit for the low-flow pneumotach is remarkable. The SEE expressed relative to the mean gasometer values results in a 5.96% error. The values begin to deviate from the line of identity at 29 $l \cdot min^{-1}$. Thus, we can conclude from these data that the low-flow pneumotach can be successfully used during rest and light exercise, where the ventilation rate does not exceed 30 $l \cdot min^{-1}$.

Figure 3 reveals that the medium-flow pneumotach ventilation volumes begin to tail-off from the line of identity at approximately 70 $l \cdot min^{-1}$. This deviation, however, is not excessive even up to approximately 100 $l \cdot min^{-1}$. The SEE expressed relative to the mean gasometer value, results in a 4.89% error. Overall, the high correlation and low SEE indicate that the medium flow pneumotach can be used successfully throughout the range of ventilation volumes from rest to moderately hard exercise, but particularly between 20 and 70 $l \cdot min^{-1}$.

The data shown in Fig. 4 for the high-flow pneumotach reveal that the SEE is larger than for the other two pneumotachs, amounting to a 9.0% error, relative to the mean gasometer value. We were unable to test the pneumotach at higher than 115 $l \cdot min^{-1}$ at STPD, and therefore cannot be sure if the linearity observed in the data will be maintained up to the 200 $l \cdot min^{-1}$ range, as advertised by the manufacturer. However, there is little reason to doubt that this will be the case, based on the fact that the data are linear starting at 30 $l \cdot min^{-1}$ up to 115 $l \cdot min^{-1}$. The increased variability at the higher flow rates is difficult to explain, other than inherent errors with increased flow rates. Certainly more data are needed to substantiate increased variability for the high-flow pneumotach.

Because of its portability, ease of use, and validity compared to a SM-MMC, the new AeroSport portable metabolic analysis system is the system of choice in application where portability, ease of use and accuracy are required. Certainly more validity studies are warranted, particularly at higher V_E and $\dot{V}O_2$ rates with different exercise protocols. Based on the results of this study, it is concluded that the TEEM 100 Metabolic Analysis System produces valid data at rest, and moderate to heavy work rates compared to a SM-MMC.

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References

AeroSport (1993) TEEM 100 Total Energy Expenditure Measurement operators manual. Ann Arbor, Mich, USA

Atwater WO, Rosa EB (1899) Description of a new respiration calorimeter and experiments on the conservation of energy in the human body. U.S. Department of Agriculture Off. Exp. Sta. Bull 63

Consolazio CF, Johnson RE, Pecora LJ (1963) Physiological measurements of metabolic functions in man. McGraw-Hill, New York

Haldane JS (1892) A new form of apparatus for measuring the respiratory exchange of animals. J Physiol (London) 13:419–430

Kane J, Jones N, Nones TE, Sutton B (1983) An evaluation of the Beckman Metabolic Measurement Cart. Beckman reprint no. 0323

Kannagi T (1983) An evaluation of the Beckman Metabolic Cart for measuring ventilation and aerobic requirements during exercise. J Cardiac Rehabil 3:38

Kleiber M (1975) The fire of life: an introduction to animal energetics, 2nd ed. Krieger, Huntington, N. Y.

Lavoisier AL, de La Place RS (1789) Memoire sur la chaleur; memoires de l'Academie Royale. Reprinted in Ostwald's Klassiker, no. 40, Leipzig, 1892

Lothian F, Farrally MR, Mahoney C (1993) Validity and reliability of the Cosmed K2 to measure oxygen uptake. Can J Appl Physiol 18:197–206

McArdle WD, Katch FI, Katch VL (1991) Exercise physiology: energy, nutrition, and human performance, 3rd edn. Lea and Febiger, Philadelphia

McNeill G, Cox MD, Rivers JPW (1987) The Oxylog oxygen consumption meter: a portable device for measurement of energy expenditure. Am J Clin Nutr 45:1415–9

Norton AC (1980) Portable equipment for gas exchange. In: Assessment of energy metabolism in health and disease. Ross Laboratories, Columbus, Ohio

Peel C, Utsey C (1993) Oxygen consumption using the K2 telemetry system and a metabolic cart. Med Sci Sports Exerc 25:396–400

Scholander PF (1947) Analyzer for accurate estimation of respiratory gases in one-half cubic centimeter samples. J Biol Chem 167:235–250

SensorMedics (1991) 2900 Metabolic Cart operator's manual, part no. 767257. Los Angeles, Calif.

Webb P, Troutman SJ (1970) An instrument for continuous measurement of oxygen consumption. J Appl Physiol 28:876

Wilmore JH, Costill DL (1974) Semiautomated systems approach to the assessment of oxygen uptake during exercise. J Appl Physiol 36:618

Wilmore JH, Davis JA, Norton AC (1976) An automated system for assessing metabolic and respiratory function during exercise. J Appl Physiol 40:619