ABSTRACT

REICHERT, B. D. A validation study of the KB1-C portable metabolic measurement system using the autocalibration feature. M.S. in Adult Fitness/Cardiac Rehabilitation, May 2000. 62 pp. (N. K. Butts)

The purpose of this study was to determine the validity of the Aerosport KB1-C portable metabolic measurement system (Aerosport, Ann Arbor, MI) using the autocalibration feature against the Quinton QMC metabolic measurement cart. Twenty healthy 18-30 year old men and women volunteered to participate in this study. All subjects were students, faculty, or staff of the University of Wisconsin-Lacrosse. Volume and gas calibrations were completed according to the specifications of the manufacturer. Validation of the QMC ventilation measurements was determined by the subjects performing an exercise test on a treadmill consisting of a standard warm-up at 3.5 mph and 10% grade, followed by 3, 5 minute workloads at a self-selected speed at inclines of 0, 2.5, and 5% grade. During this test, exhaled air was routed into the QMC and out the exhaust port into a Tissot spirometer during the final minute of each stage. Once the minute sample was collected in the Tissot, the air was forced out the exhaust port of the Tissot spirometer and through the mouthpiece of the KB1-C. Ventilation (VE) values measured by the KB1-C (STPD), QMC (BTPS), and Tissot spirometer (ATPS) were then converted to a standard volume (STPD) for comparison purposes. Comparison of physiological measures between the KB1-C and QMC was accomplished by each subject performing the same exercise test protocol as described above. During this test, exhaled air was routed into the QMC and out the exhaust port through the mouthpiece of the KB1-C for gas analysis. Repeated measures with appropriate post-hoc tests indicated no significant (p > 0.05) differences existed between the VE measures of the QMC and Tissot spirometer up to 46.8 l·min⁻¹; however, there were significant (p < 0.05) differences between the Tissot vs KB1-C at all workloads. When physiological measures were compared between the KB1-C and QMC, VE data were not significantly (p > 0.05) different. No significant (p > 0.05) differences were found for measures of \( F_eO_2 \); however, \( F_eCO_2 \) values were significantly (p < 0.05) different with both \( F_eO_2 \) and \( F_eCO_2 \) values produced by the KB1-C consistently lower than the QMC. Oxygen consumption and \( VCO_2 \) data were both found to be significantly (p < 0.05) different, which produced similar RER values as the reference system, but cannot be termed accurate due to the error in both \( VO_2 \) and \( VCO_2 \). It was concluded that the KB1-C should not be utilized using the autocalibration procedure in a research capacity due to significant inaccuracy in measurements provided by the unit.
A VALIDATION STUDY OF THE KB1-C PORTABLE METABOLIC MEASUREMENT SYSTEM USING THE AUTOCALIBRATION FEATURE

A THESIS PRESENTED TO THE GRADUATE FACULTY UNIVERSITY OF WISCONSIN-LA CROSSE

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE MASTER OF SCIENCE DEGREE

BY BRENT REICHERT

MAY 2000
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We recommend acceptance of this thesis in partial fulfillment of this candidate's requirements for the degree:

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The candidate has successfully completed the thesis final oral defense.

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CHAPTER I

INTRODUCTION

The measurement of oxygen consumption ($\text{VO}_2$) is a vital tool in the study of physical activity. It is used to indirectly determine the energy costs of exercise, evaluate the effectiveness of training programs, determine aerobic fitness, and provide an indispensable tool for research. It is commonly measured by determining the volume of expired air as well as the percentages of oxygen and carbon dioxide in the inhaled and exhaled air. Once this information has been obtained, the actual $\text{VO}_2$ can be calculated.

Until recently the equipment most commonly used to determine $\text{VO}_2$ has been confined to a laboratory due to its large size, power requirements, lack of mobility, and inability to be used in harsh environmental conditions. Unfortunately, the laboratory cannot reproduce the environment in which many activities take place (e.g., rock climbing, ice skating, and cross country skiing). Studying the energy costs of these activities may be difficult, if not impossible. The one method that can be utilized for these conditions is the use of Douglas bags or meteorological balloons to collect expired air. The gas must then be analyzed in the laboratory; however, this is a laborious and time consuming technique. Recently, a portable weather resistant unit capable of measuring $\text{VO}_2$ that can be carried or worn by a subject without hindering their performance has been developed by Aerosport, Inc. (Ann Arbor, MI). If this instrument is accurate, the scope of research could be greatly widened, and the boundaries of the laboratory eliminated.
The Aerosport KB1-C is a portable metabolic measurement system that can produce the same information obtained from the larger metabolic equipment previously mentioned. The KB1-C is 9” x 4.75” x 3” (LxWxH) and weighs approximately 2.2 lb. This small size allows the KB1-C to be carried by the subject via a harness or belt during activity; however, the validity of these units has been in question.

According to the manufacturer of the KB1-C, the accuracy of the gas analyzers is ± 0.08% and ± 0.05% for oxygen and carbon dioxide, respectively, and the pneumotachometer is accurate to ± 0.40 L·min⁻¹. This study was conducted to determine the validity of the KB1-C using the autocalibration feature against the Quinton QMC metabolic cart (Quinton, 1994).

**Statement of the Problem**

The purpose of this study was to determine the validity of the Aerosport KB1-C portable metabolic measurement system using its autocalibration feature.

**Null Hypothesis**

The first hypothesis of this study was that there will be no significant differences in minute ventilation volumes (VE) in L·min⁻¹, gas fractions of expired oxygen (F̵E̵O₂), gas fractions of expired carbon dioxide (F̵E̵C̵O₂), oxygen consumption (VO₂) in L·min⁻¹, carbon dioxide production (VCO₂) in L·min⁻¹, and respiratory exchange ratio (RER) between the KB1-C, using the autocalibration feature, and the QMC metabolic cart. The second hypothesis was that there will be no significant differences in VE (L·min⁻¹) among
the KB1-C using the autocalibration feature, QMC metabolic cart, and the Tissot spirometer (developed by Warren E. Collins, Inc., Braintree, MA).

Assumptions

The following were assumptions of this study:

1. The Quinton metabolic cart is a valid and reliable reference.
2. All testing procedures were administered consistently.
3. Steady state values were obtained from all subjects during gas measurement periods.
4. The expired gas from the Tissot spirometer adequately simulated exhalations by a subject.
5. The residual air contained in the Tissot spirometer has a negligible effect on the data collected.
6. The gas samples taken for analysis represented 1 minute of expired gas.

Delimitations

1. Subjects included apparently healthy volunteers from the University of Wisconsin-LaCrosse ranging in age between 18-30 years.
2. Only measures of \( \text{VO}_2 \) in \( \text{L} \cdot \text{min}^{-1} \), \( \text{VCO}_2 \) in \( \text{L} \cdot \text{min}^{-1} \), \( \text{VE} \) in \( \text{L} \cdot \text{min}^{-1} \), \( \text{F}_{\text{E}}\text{O}_2 \), \( \text{F}_{\text{E}}\text{CO}_2 \), and \( \text{RER} \) were compared between the QMC and KB1-C.
3. All data were analyzed and calculated by the same investigators.

Limitations

A limitation of this was that gas measured by the KB1-C from the Tissot spirometer was not directly exhaled by a human subject.
Definition of Terms

Carbon Dioxide Production (VCO₂) - the volume of carbon dioxide produced by the body per minute (L·min⁻¹ at STPD).

FₑCO₂ - fractional concentration of carbon dioxide in an expired gas.

FₑO₂ - fractional concentration of oxygen in an expired gas.

KB1-C Portable Metabolic Measurement System - a portable system developed by Aerosport Incorporated (Ann Arbor, MI) to measure respiratory and metabolic data during exercise.

Minute Ventilation Volume (VE) - the amount of gas expired in 1 minute (L·min⁻¹ at STPD).

Oxygen Consumption (VO₂) - the volume of oxygen consumed by the body per unit of time (L·min⁻¹ at STPD).

QMC Metabolic Cart - a computerized, automated system developed by the Quinton Instrument Company (Seattle, WA) to provide respiratory and metabolic assessment during exercise.

Respiratory Exchange Ratio (RER) - the ratio of carbon dioxide production to oxygen consumption over the same period of time.

STPD - standard temperature (0°C) and pressure (760 mmHg) as a dry gas. Used for expressing the volume of gases exchanged in metabolic measurements (i.e., VO₂, VCO₂, and VE).
**Steady State** - the point at which oxygen consumption plateaus (failure to increase by 150 ml-min\(^{-1}\)) at a certain work rate, where the demand for oxygen by the working muscles is met by the ability of the body to supply it.

**Tissot Spirometer** - a calibrated 120 L. cylinder sealed from outside air by using a water seal in a second cylinder manufactured by Warren E. Collins, Inc. (Braintree, MA). Used as a standard to measure gas volumes.
CHAPTER II
REVIEW OF RELATED LITERATURE

Introduction

Advances in technology have made it possible to measure respiratory and metabolic functions during almost any activity by developing lightweight portable equipment. Oxygen consumption (VO₂), one of the most important metabolic measures, is a key component to research in the sport sciences, to the clinical management of patients, and for the development of training programs for elite athletes (Peel & Utsey, 1993). Oxygen consumption is defined as the volume of oxygen consumed by the body per unit time (Brooks & Fahey, 1984). Maximal oxygen consumption (VO₂max) is also one of the most widely used measures of cardiovascular endurance (ACSM, 1995).

To determine VO₂, several measurements must be made. Minute ventilation (VE) must be determined at a standard temperature (0°C) and pressure (760mmHg) of a dry gas (STPD). Fractional concentrations of expired oxygen (FEO₂), fractional concentrations of expired carbon dioxide (FE CO₂), barometric pressure (PB), temperature (T), and time must also be determined. With this information the volume of carbon dioxide produced (VCO₂) and the respiratory exchange ratio (RER) can be determined.

The measurements of PB, T, and time are easily obtained from common instruments including mercury barometers, thermometers, and stop watches; however, the measurements of VE, FEO₂, and FE CO₂ are where modern advances are taking place. The invention of metabolic carts, where all equipment to determine these measures is
integrated into one unit, provided a compact, convenient, and user friendly system. Now, technology has provided even more advancement by producing a system similar to a metabolic cart, but compact and lightweight enough to be carried by an individual during almost any activity. This eliminates the restrictions of the metabolic cart imposed by its size, power requirements, and inability to be used in harsh environmental conditions (i.e., rain and snow).

The Aerosport KB1-C is one such portable unit. In this chapter, indirect calorimetry, the development of automated systems to measure VO₂, and the development of the KB1-C portable metabolic measurement system are described.

**Indirect Calorimetry**

Oxygen consumption has become one of the most widely used measurements of caloric expenditure during activity. Energy metabolism in the body depends on the utilization of oxygen and the production of carbon dioxide; therefore, an indirect estimation of energy metabolism can be determined by measuring an individual’s oxygen consumption during steady state exercise (McArdle, Katch, & Katch, 1991). This technique is termed indirect calorimetry. There are two methods for performing indirect calorimetry: open circuit and closed circuit. Since both the QMC and the KB1-C utilize open circuit spirometry, closed circuit spirometry will not be discussed. Open circuit spirometry involves the inspiration of ambient air and routing the exhaled air into a unit for fractional gas concentration and volume analysis.

The KB1-C and QMC measure fractional gas concentrations of oxygen and carbon dioxide with rapid responding oxygen and carbon dioxide gas analyzers and ventilation by
a pneumotachometer. The machines differ by how the equipment is arranged. The KB1-C utilizes the pneumotachometer and a gas sampling line in the mouthpiece. The sampling line routes the gas into the unit worn by the subject for gas analysis. The QMC utilizes a Hans-Rudolph valve and low resistance tubing to route the gas to the pneumotachometer upon entering the machine, and then to a mixing chamber to ensure adequate mixing of the gases before being sampled by the gas analyzers.

Development of Automated Systems Used to Measure VO₂

Prior to the 1950's, the primary method for determining oxygen consumption, and considered by many to be the standard method of measurement for validation purposes today, was the Douglas bag method (Beaver, Wasserman & Whipp. 1973; Consolazio, Johnson, & Pecora, 1963; Wilmore & Costill, 1974). This method uses a Douglas bag or similar device, such as a meteorological balloon, to collect samples of expired gas. Once collected, a small sample of gas is removed and analyzed for oxygen and carbon dioxide content by chemical or electronic gas analyzers. Volume measurement is then carried out by emptying the contents of the bag through a Parkinson-Cowan type gas meter or into a Tissot spirometer. This method is highly accurate, but is very time consuming and requires specialized training. To simplify the process of measuring oxygen consumption, automated systems were developed which could acquire data rapidly.

The development of rapid responding gas analyzers was one of the first breakthroughs that made automated systems possible. Such an analyzer for measuring oxygen was developed in 1946 (Pauling, Wood, & Sturdivant, 1946). In the 1950's carbon dioxide could be analyzed rapidly by utilizing an infrared gas analyzer (Brown,
1952). These analyzers were then integrated with an electronic gas volume measurement device and a computer. This created a complete system for measuring metabolic and respiratory function (Johnson et al., 1967; Kannagi et al., 1983; Norton, 1982; Versteeg & Kippersluis, 1989; Wilmore & Costill 1973; Wilmore & Costill, 1974; Wilmore, Davis, & Norton, 1976). Studies of these systems appeared in the literature, but only the calibration procedures used were usually reported (Johnsr et al., 1967; Wilmore & Costill, 1973; Wilmore & Costill, 1974). Reliability and validity were determined for two systems using the Douglas bag or similar technique. The Beckman metabolic measurement cart (MMC) was studied by Kannagi et al. (1983) and Wilmore et al. (1976), and the MMC Horizon system was studied by Norton (1982) and Versteeg and Kippersluis (1989).

Johnson et al. (1967)

In 1967, Johnson et al. described one of the first systems to measure VO2. This system utilized a Tissot spirometer for ventilation volume measurement at rest, a Kofranyi-Michaelis respirometer for moderate activity, and a low-resistance Parkinson-Cowan CD-4 dry gas meter for high level activity. Metalized bags impermeable to O2, CO2, and water vapor were used to collect and store expired air samples. Oxygen and CO2 content were then measured by a paramagnetic O2 meter and a thermal conductivity CO2 meter.

The gas analyzers used for measuring expired air were calibrated with room air and a gas sample consisting of O2, CO2, and N2 which had been previously analyzed with the Haldane apparatus. The sample calibration gas was introduced into the system after the room air had been analyzed and prior to the introduction of the expired gas samples.
Percentages of $O_2$ and $CO_2$ were calculated from calibration curves obtained from the procedure.

Wilmore and Costill (1973)

Wilmore and Costill (1973) utilized the Haldane transformation to determine the extent to which the calculation of $VO_2$ was influenced by $N_2$ retention. They utilized a Daniels-type respiratory valve (Daniels, 1971), two Parkinson-Cowan CD-4, high-velocity, low-resistance dry gas meters to measure inspiratory and expiratory ventilation volumes, a mixing chamber, a Med-Spec mass spectrometer (model MS-8) to measure $O_2$ and $CO_2$ gas percentages, and a Raytheon Computer (Model 703) to analyze the data. One minute samples were also collected and analyzed by a Beckman E-2 $O_2$ analyzer and a Beckman LB-1 $CO_2$ gas analyzer.

Calibration procedures were carried out at the beginning and the conclusion of the study. The gas meters were calibrated against a 120 L Tissot spirometer at flow rates of 5, 20, 60, and 100 L·min$^{-1}$. The mass spectrometer was calibrated between workloads by measuring room air and mixed gases of known concentration as determined by the micro-Scholander technique (Scholander, 1947).

Wilmore and Costill (1974)

In 1974, Wilmore and Costill used a relatively inexpensive system to measure $VO_2$. This system consisted of a Parkinson-Cowan CD-4 gas meter to measure $VE$, a three-way valve for the allocation of gas samples, a Hewlett-Packard 9810 programmable calculator for data analysis, a Beckman OM-11 $O_2$ analyzer, and a Beckman LB-2 $CO_2$ analyzer.
A two-liter rubber bag filled with one of several calibration gases was used to calibrate the gas analyzers. The rubber bag was connected to one end of a two-way stopcock. The stopcock was positioned close to the mixing chamber in-line with the three-way gas-sampling valve that was also connected to the mixing chamber. This setup was very similar to the actual gas collection procedure used during the test, and allowed the calibration gases to pass through all the fittings and joints, which helped to detect any potential leaks in the system. A 120 L Tissot spirometer was used to calibrate the gas meter used in this system at flow rates ranging from 20-200 L-min^-1.

One of the major drawbacks of the study was that only the gas concentrations were compared between the two methods. It was found that the gas concentrations were nearly identical between the two, but since VE comparisons were not made, the entire system could not be validated.

Wilmore et al. (1976)

The Beckman MMC was compared to the two systems previously described by Wilmore and Costill (Wilmore & Costill, 1973; Wilmore & Costill, 1974). Ventilation was measured by the MMC by a turbine, and Beckman OM-11 and LB-2 gas analyzers were used to measure O₂ and CO₂, respectively. A 500 ml-min^-1 sample of expired air was drawn constantly from the mixing chamber. The sample would flow through a drying column and into the gas analyzers, then return to the mixing chamber prior to passing through the turbine for volume measurement.

Calibration of the gas analyzers was carried out before and after each test using calibration gases analyzed by the micro-Scholander technique. A 120 L Tissot spirometer
was used at the beginning and conclusion of the study to calibrate the volume transducer of the MMC and the two Parkinson-Cowan gas meters. The Tissot spirometer, two gas meters, and the MMC volume transducer were all placed in series. Air was then pulsed out of the Tissot spirometer, through the two gas meters, and finally through the MMC volume transducer. It was found that the Parkinson-Cowan gas meter used in the setup similar to the computerized system used by Wilmore and Costill in 1973 was the least stable, due to underestimating the lower volumes.

In 49 of the 122 tests, all three systems were used simultaneously. In the remaining 63 tests, the MMC and computerized system were used. No significant differences were found between the values of $F_{E}O_2$ and $F_{E}CO_2$ among the three systems. Ventilation measures were all nonsignificant, except for the lowest two workloads compared between the MMC and the computerized system. Oxygen consumption measures between the three systems were significantly different only during two low-level workloads, and significantly different during the lowest five workloads when comparing the MMC to the computerized system. No significant differences were found between the three systems for RER.

Kannagi et al. (1983)

Kannagi et al. (1983) performed this investigation on the Beckman MMC to improve upon the study performed by Wilmore et al. (1976). Wilmore et al. connected the systems used in series, which may have produced high resistance to the flow of air. Instead, Kannagi et al. compared the MMC to a method established by Bruce, Kusumi, and Hosmer (1973), which utilized neoprene balloons to collect the gas samples, a
respiratory test meter by American Meter Company (model DTM-115) to measure gas volume, and Beckman OM-11 and LB-2 gas analyzers to measure O₂ and CO₂, respectively.

Calibration of the gas analyzers was performed by analyzing two reference gases, previously determined by the micro-Scholander method, and room air. In addition, no significant differences were found when the analyzers in both systems were compared at O₂ and CO₂ gas concentrations in the clinical range.

Measures of VO₂, VCO₂, VE, and RER were also compared between the MMC and manual method. Eight subjects performed two submaximal and two maximal incremental treadmill exercise tests, with each test measured by the MMC and the manual method. Comparisons were made with the measurements recorded during the third minute of each stage.

Reliability was tested by comparing the data obtained from the two systems at similar workloads. No significant differences were found for VO₂, VCO₂, VE, and RER, thus the researchers concluded the two systems were reliable.

Validity was tested by correlating the values recorded by the MMC to the manual method during the submaximal tests, and then the maximal test. A high correlation was found between the two systems for VE (.97), VO₂ (.98), and VCO₂ (.99). Respiratory exchange ratio correlated lower (.93). A significant difference was found, however, between the two systems for VO₂ and VCO₂, with the MMC consistently producing greater values than the manual method.
Norton (1982)

Norton (1982) evaluated the MMC Horizon system, the successor to the Beckman MMC as described by Wilmore et al. (1976). This unit was the first to integrate all instruments for data collection into one unit, instead of a collection of individual instruments. Ventilation is measured by a jewel-mounted turbine, which incorporates electro-optical detectors, placed on the outlet of the mixing chamber. Gas concentrations are determined by drawing a constant 500 ml·min⁻¹ sample of gas from six sampling lines in the mixing chamber through the O₂ and CO₂ analyzers.

Calibration of the MMC Horizon gas analyzers was performed by sampling pure N₂ and a calibration gas analyzed by the micro-Scholander method. The volume transducer was calibrated by the manual delivery of eight strokes of a pump at each of three flow rates. Calibration was then completed by the microprocessor performing a linearization of the volume.

The MMC Horizon was evaluated by comparing it to a reference system consisting of gas collection in meteorological balloons and analyzing the samples with a Tissot spirometer and OM-11 and LB-2 gas analyzers. Gas samples from eight subjects were collected at rest and during steady-state exercise on a bicycle ergometer. The two systems were connected in series with the balloon attached to the outlet of the mixing chamber of the MMC Horizon. A high correlation was found between the two systems for VE (.9973), VO₂ (.9930), and VCO₂ (.9979). One limitation of this study was the maximal VE recorded was 85 L·min⁻¹ (BTPS), which is below the expected maximal VE.
Versteeg and Kippersluis (1989)

The MMC Horizon, previously described by Norton (1982), and the EOS-Sprint systems were compared to the Douglas bag method by Versteeg and Kippersluis in 1989. The EOS-Sprint system measures VE by a pneumotachometer, and gas concentrations are continuously sampled from a mixing chamber and analyzed by a paramagnetic O\textsubscript{2} analyzer and an infrared absorption CO\textsubscript{2} analyzer. The Douglas bag method involves collecting gas samples into bags and analyzing them after the completion of the test. Gas analysis was performed by drawing a gas sample from the bag with a centrifugal pump and analyzing it with a Servomex 570A Sybron paramagnetic O\textsubscript{2} analyzer and a Godart 146 infrared CO\textsubscript{2} analyzer. Gas volume was measured with a Schlumberger gasometer.

The gas analyzers of the EOS-Sprint system were calibrated by sampling two gases analyzed by the micro-Scholander method. The pneumotachometer was calibrated with a manual one liter syringe provided with the machine. Calibration of the gas analyzers used for the Douglas bag method were also checked by sampling two reference gases analyzed by the micro-Scholander method.

Comparisons were made during steady state exercise, incremental exercise to maximal intensity, and single-step exercise all performed on a bicycle ergometer. Gas samples were either collected in bags or exhaled directly into the one of the systems. When oxygen consumption values of the MMC Horizon and EOS-Sprint systems were then compared to the Douglas bag method, no significant differences were found.

These new automated rapid responding systems were a huge leap forward for the study of physical activity; however, they too had their drawbacks. The large size and
power requirements restricted these systems to be utilized mainly in a laboratory. They were also unable to be used in many outdoor activities due to their inability to resist rain and other harsh environmental conditions. Left was the need for a portable weather resistant version of the large automated systems.

**Development of Portable Metabolic Measurement Systems**

Recently, several companies have developed light weight, weather resistant, portable versions of the automated systems to measure VO2. With these systems, measurements can be taken during any activity where the subject is able to carry the unit. However, the accuracy of the gas and volume analyzers may have been compromised when they were scaled down. Therefore, the validity of these systems has been questioned. The following is a review of studies testing the validity of various portable systems.

**Cosmed K2**

The Cosmed K2 system consists of a soft facemask with a turbine attached to measure VE, a transmitter and battery worn on a chest harness, and a receiver unit. Oxygen concentrations are measured by exhaled air traveling down a capillary tube to the transmitter unit, which contains a polargraphic electrode O2 analyzer. Signals from the portable unit are transmitted to the receiver where data processing and display take place. The unit does not contain a CO2 analyzer, so the unit assumes a RER of one for the calculation of VO2. Calibration of the O2 analyzer was performed by the unit sampling room air, and the turbine is calibrated using a three liter syringe.
In 1992 Kawakami, Nozaki, Matsuo, and Fukunaga tested the validity of the Cosmed K2 portable metabolic measurement system against the Douglas bag method. Eight subjects performed a maximal graded exercise test in a bicycle ergometer while exhaling through the mask and into a Douglas bag. The exercise protocol consisted of an initial workload of .5 kp with increases of .5 kp every minute for men and .25 kp for women, until exhaustion. The exhaled gas sample was later analyzed by forcing the gas out through a Max Planck Respiration Gasometer and gas concentration analyzer (1H21, NEC San-ei, Japan) to calculate VE and VO\textsubscript{2} for each minute.

Kawakami et al. (1992) found that the VE data from the K2 differed significantly from the Douglas bag system during the third minute. No significant differences for VE were found for the other 15 minutes of data. Therefore they concluded that the Cosmed K2 accurately measured VE up to 180 L·min\textsuperscript{-1}. Oxygen consumption data revealed that the K2 system differed significantly from the Douglas bag system at rest and during the 2\textsuperscript{nd}, 6\textsuperscript{th}, 7\textsuperscript{th}, 8\textsuperscript{th}, and 9\textsuperscript{th} minutes. The K2 consistently overestimated VO\textsubscript{2}, likely due to the difference in the method of calculating VO\textsubscript{2}. The Douglas bag method calculates VO\textsubscript{2} by using VE, F\textsubscript{E}O\textsubscript{2}, and F\textsubscript{E}CO\textsubscript{2}, while the K2 uses F\textsubscript{E}O\textsubscript{2} and VE and the assumption that RER is equal to one. However, if this were the case, there would have been a relationship between calculated VO\textsubscript{2} and RER values, which was not found. They concluded that the differences may have been attributed to methodological errors that occurred during air collection. Significant differences were not found for the remaining data, so they concluded that the K2 may be used as a tool for research in the field of exercise science.
Peel and Utsey (1993) compared the Cosmed K2 system to a Gould 9000PC MMC (Dayton, OH) during two graded treadmill exercise tests at three miles per hour and 0, 5, 10, and 15% grade. The MMC measured VO2 by analyzing exhaled air from a subject through a two-way breathing valve and rubber hose. Once in the unit, VE is measured by a 10 L spirometer, and gas concentrations are measured by a paramagnetic analyzer (O2) and an infrared absorption analyzer (CO2). Calibration of the Gould 9000PC gas analyzers was performed by sampling room air and gas mixtures of 0% O2 and 5.04% CO2. The spirometer was calibrated using a 3 L syringe.

The K2 was used to measure VE and VO2 during one treadmill test, and the MMC was used for the other. When compared, no significant differences were found between the VE measurements of the two machines. Oxygen consumption values produced by the K2 were found to be significantly lower than the MMC. Even when the K2 values were recalculated with the RER values from the MMC, a significant difference existed.

Therefore, these conclusions agree with Kawakami et al. (1992) that the method of VO2 calculation by the K2 is not the source of error. It was concluded that the probable source of error was due to the method of collecting or analyzing expired air. The systems were not connected in series, which would have been the optimal way to compare the two systems.

Crandall, Taylor, and Raven (1994) tested the validity of the K2 to a standardized breath-by-breath (BBB) system. The BBB system consisted of a turbine volume transducer (Alpha Technologies, VVM) for the measurement of VE, a calibrated mass spectrometer (Perkiin-Elmer, MGA-1100) for O2 and CO2 analysis, and a laboratory mini
computer (DEC, M1NC23) for data computation. Fifteen subjects performed two maximal graded exercise tests on a treadmill following the Bruce protocol. One test measured by the K2 and the other by the BBB system. The order of the equipment used was randomized.

At each stage of the exercise test, heart rate did not significantly differ between the two tests, so it was concluded that the work performed during each test was similar. Ventilation volumes were found to be significantly larger with the K2 system than with the BBB system, which is in contrast to the studies discussed previously. Kawakami et al. (1992) and Peel and Utsey (1993) concluded that VE was accurately measured by the K2. Crandall et al. (1994) concluded that the inaccuracy of the VE measurements was likely due to the differences in external dead space of the equipment used to collect the gas samples. The K2 face mask covers the nose and mouth, so it has a much larger dead space. The BBB system uses a smaller traditional mouthpiece, so less CO\textsubscript{2} will be reinspired, resulting in a reduced VE. When VO\textsubscript{2} data were analyzed, the K2 system consistently underestimated VO\textsubscript{2} at low workloads, and overestimated it during higher workloads, compared to the BBB system. This was expected by the author, due to the K2 system lacking a CO\textsubscript{2} analyzer; however, none of the differences were significant. Crandall et al. also corrected the VO\textsubscript{2} values obtained from the K2 system with the RER derived from the BBB system, but since no significant differences existed before correction, the difference was not statistically significant.
Cosmed K4

The Cosmed K4 was developed to eliminate the major limitation of the K2. The K4 was equipped with an infrared electrode to analyze CO₂ in the portable unit. This allows the system to measure VCO₂ and RER, which was not possible with the K2. The rest of the system remained the same.

Hausswirth, Bigard, and LeChevalier (1997) compared the Cosmed K4 to the Medical Graphics CPX (Saint Paul, MN) MMC. Seven subjects performed two maximal graded exercise tests on a treadmill. Workloads of 25, 50, and 75% of max, along with the maximal intensity were used for statistical analysis. During one test the K4 was used, and the CPX for the other. Before each test, the CPX zirconium cell O₂ analyzer and infrared CO₂ analyzer were calibrated by sampling a reference gas of 12.01% O₂ and 5.01% CO₂, and the flowmeter turbine was calculated using a 3 L syringe.

The results show that the K4 did not differ significantly from the CPX for VO₂, VCO₂, RER, or VE at any workload. The researchers concluded that the K4 can be used as an accurate tool for research of submaximal and maximal exercise.

CORTEX X1

The CORTEX X1 system is similar to the Cosmed K4. The arrangement of equipment, along with the devices to measure flow and CO₂ are identical. The one difference is the use of a zirconium O₂ analyzer, which is much less sensitive to changes in temperature compared to the polarographic analyzer.

The validity of the CORTEX X1 was studied by Schulz, Helle, and Heck (1997). The OXYCONgamma, a standardized breath by breath system, was used as the reference.
This consisted of a differential paramagnetic sensor and an infrared analyzer for O₂ and CO₂ analysis, respectively. Ventilation volume was measured with turbine flowmeter. Gas analyzer calibration was performed by sampling room air or a calibration gas (16% O₂, 5% CO₂, and 79% N₂). A 3 L syringe was used to calibrate the turbine flowmeter.

Seven female and eight male subjects performed two graded exercise tests on a bicycle ergometer. Workloads consisted of 3 minute stages beginning with 50W and increasing by 50W increments until volitional fatigue. Statistical analysis of the data collected during the last 30 sec of each stage show no significant difference between VE, VO₂, and VCO₂ measured by the CORTEX XI and the OXYCONgamma.

**Aerosport KB1-C**

The KB1-C was developed by Aerosport, Inc. (Ann Arbor, MI) as a totally portable system for measuring respiratory and metabolic parameters during exercise. The system features a differential pressure pneumotachometer for the measurement of VE, and electronic gas analyzers for the measurement of FE₉O₂ and FE₉CO₂, yet only weighs one kilogram. This allows measurements to be taken during any activity where the subject is able to carry the unit.

King, McLaughlin, Howley, Bassett, and Ainsworth (1999) tested the validity of the KB1-C against the Douglas bag method. Nine subjects performed cycle ergometry at workloads of: rest, 50W, 100W, 150W, 200W, and 250W for 5 minutes each. Gas samples were collected during the last 2 minutes of each stage. When compared for values of VE, VO₂, VCO₂, FE₉O₂, FE₉CO₂, and RER, the investigators found a nonsignificant difference in values between the two methods for VE, VO₂ and VCO₂ at
100, 150, and 250 W, while the KB1-C was significantly different at rest, 50, and 200 W. Measures of $F_EO_2$ and $F_ECO_2$ were found to be significantly different at rest and 150 W, but not at 50, 100, 200, and 250 W. Respiratory exchange ratio measurements were found to be significantly different at 100, 150, and 200 W, while no significant difference was found at rest, 50, and 250 W. The authors concluded that the KB1-C could be used to accurately measure VO$_2$ between 1.5 and 3.5 L·min$^{-1}$, while using the pneumotachometer at the medium flow setting.

This scaled down version of metabolic cart has been validated in one study; however, the Aerosport Teem 100, predecessor to the KB1-C, has been tested repeatedly for validity. Descriptions of these studies will follow.

**Aerosport Teem 100**

The Aerosport Teem 100 is the predecessor to the KB1-C and functions similarly. Three studies investigated the validity of the unit. Darby, Peng, and Liu (1997) compared the Aerosport Teem 100 against the Sensormedics 2900 metabolic measurement cart (MMC). Nineteen male and 22 female subjects performed a maximal graded exercise test on a motor driven treadmill. Measures of VO$_2$, VE, $F_EO_2$, and $F_ECO_2$ were taken by each unit simultaneously during each minute of the test. The results showed that there were no significant differences between the measures determined by the two machines until after 5 minutes of exercise. After 5 minutes, VO$_2$ and VE were significantly overestimated by the Teem 100, while $F_EO_2$ and $F_ECO_2$ were underestimated. They concluded that the Teem 100 was useful for demonstration and instructional purposes, but could not be used accurately at higher workloads.
The Aerosport Teem 100 was also studied for validity by Novitsky, Segal, Chatr-Aryamontri, Guvakov, and Katch in 1994. During an incremental cycle ergometer test consisting of workloads of 0, 25, 50, 75, 100, 125, and 150W, \( \text{VO}_2 \) was compared between the Teem 100 and the Sensormedics 2900 MMC. To study VE the Teem 100 was compared to a 120 L Tissot spirometer during the same test protocol. They found that the \( \text{VO}_2 \) values were not significantly different during all workloads except for 100W. From this they concluded that the Teem 100 produces valid \( \text{VO}_2 \) data at low to moderate workloads. Ventilation measures were highly accurate and not significantly different at any workload.

Wideman et al. (1996) compared the Aerosport Teem 100 to the Rayfield system during incremental and continuous load exercise by 12 subjects. The incremental exercise consisted of running and stepping protocols. The running protocol consisted of treadmill exercise at 110 m-min\(^{-1}\) and increasing by 10 m-min\(^{-1}\) every 3 minutes until volitional fatigue. The stepping protocol consisted of stepping on an 8 inch step at a rate of 15 steps-min\(^{-1}\) and increasing by 2.5 steps-min\(^{-1}\) until volitional fatigue. Continuous exercise consisted of running for 30 min at 60% heart rate (HR) max, 90% HR max, and at a blood lactate concentration of 4.0 mM. Values of \( \text{VO}_2 \), \( \text{VCO}_2 \), VE, RER, \( \text{F}_\text{E} \text{O}_2 \), and \( \text{F}_\text{E} \text{CO}_2 \) were taken each minute during both incremental and continuous exercise. The results showed a significant difference in all values during incremental and continuous workloads between the Teem 100 and the Rayfield system. At low workloads the Teem 100 had a tendency to overestimate \( \text{VO}_2 \), \( \text{VCO}_2 \), RER, and \( \text{F}_\text{E} \text{CO}_2 \), while at higher workloads these measures were underestimated. Directional measurement errors for VE
and $F_iO_2$ were not reported. The authors concluded that the measurements provided by
the Teem 100 were inaccurate.

Summary

The preceding review of related literature has shown that there is a need for
portable metabolic measurement systems for use in conditions where the larger systems
are unable to be utilized. Portable systems that have been tested for validity have
produced mixed results. The results of the studies testing the Teem 100, predecessor to
the KB1-C, indicate that it cannot be considered a valid system from the available
literature. It also explained that only one study has tested the validity of the KB1-C.
Therefore, the purpose of this study was to test the validity of the KB1-C portable
metabolic measurement system using the autocalibration.
CHAPTER III

METHODOLOGY

Subject Selection

Twenty subjects, consisting of apparently healthy 18-30 year old men and women, volunteered to participate in this study. All subjects were students, faculty, or staff of the University of Wisconsin-LaCrosse.

Preparatory Procedures

Subjects were informed of the testing procedures and objectives by the primary investigator, which were approved by the Institutional Review Board at the University of Wisconsin-LaCrosse. Informed consent was obtained (see Appendix A), and subjects were asked to dress appropriately for exercise, avoid strenuous physical activity for at least 6 hours prior to the testing, and not to consume food at least 2 hours prior to testing.

Calibration Procedures

The KB1-C can be calibrated by two methods, manual calibration and autocalibration. The manual calibration feature requires the infusion of known gas concentrations of oxygen (O₂) and carbon dioxide (CO₂) into the gas analyzers for calibration.

For simplicity in the field, the KB1-C has an autocalibration feature, which does not require the use of gas samples. This was the method utilized in this study. Autocalibration was accomplished by the unit setting the carbon dioxide gain automatically by utilizing an electro-optic calibrator that simulates an actual calibration gas.
in the analysis cell, and calibrated oxygen by sampling room air and assuming it contained 20.93% O₂. The pneumotachometer of the KB1-C was calibrated by entering ambient temperature and barometric pressure. The expected measures of ventilation (VE) would fall into the range of the medium flow setting (10-120 L-min⁻¹), so the pneumotachometer was then adjusted accordingly. Then, a recommended amount of air (21 liters) for the medium flow pneumotachometer was manually infused through the unit at a standard flow rate, as indicated by a reading of three to seven on a zero to nine flow indicator scale presented on the screen of the unit, using a three liter syringe. If the KB1-C detects greater than a 10% error, a prompt appears to repeat the volume calibration process.

The QMC gas analyzers were calibrated by using the gas calibration program of the unit and two calibration gases analyzed by the micro-Scholander technique (Scholander, 1947). The pneumotachometer of the QMC was calibrated by using the pneumotachometer calibration software. This was accomplished by entering ambient measures of temperature, barometric pressure, and relative humidity. Then, three liters of air were introduced through the pneumotachometer at various flow rates using a three liter syringe. These flow rates were determined by pushing the plunger in at a speed that elicits flow levels (as presented on the monitor) along the range of expected volumes. The software then calibrates the measures to equal three liters. All calibration procedures were performed with the equipment placed in series, as it would be during the testing procedures, with the mouthpiece of the KB1-C placed on the exhaust port of the QMC.
Testing Procedures

The subject performed two exercise tests on a motor driven treadmill on two separate visits. During both tests, the subject walked on a motor driven treadmill at 3.5 miles per hour and 10% grade as a warm-up. The speed was increased to a comfortable running pace selected by the subject and the grade reduced to 0%. The grade was then increased by 2.5% every 5 minutes. Steady state measurements were taken between the fourth and fifth minutes until the subject completed three workloads or until they were no longer able to continue. Steady state was defined as a plateau of oxygen consumption (failure to increase by 150 ml·min⁻¹) at the particular workload.

Two tests were performed for the purpose of this study. One test was to compare values of oxygen consumption (VO₂), carbon dioxide production (VCO₂), VE, respiratory exchange ratio (RER), fractional concentrations of O₂ (FₑO₂), and fractional concentrations of CO₂ (FₑCO₂) between the KB1-C and QMC. These values were obtained simultaneously by the two machines. Measurements were taken by the QMC and the KB1-C by routing the exhaled air of the subject, via a Hans Rudolph valve and low resistance tubing, into the QMC and out the exhaust port where the mouthpiece of the KB1-C was placed. This test was the main focus of the study.

The second test compared VE measures between the KB1-C, QMC, and Tissot spirometer. This test was performed to test the validity of the VE measures of the QMC against the Tissot spirometer, which is a standard to measure gas volumes. Ventilation measures were first obtained using the QMC metabolic cart via the subject breathing through a Hans Rudolph valve and routing the gas to the QMC with low resistance tubing.
The expired gas then traveled out the exhaust port and was routed into a Tissot spirometer after a starting measure of volume contained in the spirometer was obtained. Once the full volume of the one minute sample was in the spirometer, the intake valve was closed and an end measure of volume was obtained. The expired volume was later determined by calculating the difference between start and end volume measurements. The volume of air in the spirometer was then measured by the KB1-C by placing the mouthpiece on the exhaust port of the Tissot spirometer and forcing the gas out by manually pushing the bell of the spirometer down in a pulsing motion to simulate a subject’s expiration pattern. The pneumotachometer on the KB1-C was adjusted to the medium flow setting to suit the expired ventilation volumes of the subject.

Statistical Analyses

Minute values of VO\(_2\), VCO\(_2\), VE, RER, FeO\(_2\), and FeCO\(_2\) obtained from the QMC and the KB1-C were compared by using a 2 x 4 ANOVA with repeated measures and Pearson product-moment correlations. Values of VE obtained from the QMC, KB1-C, and Tissot spirometer during the second test were compared using a 3 x 4 ANOVA with repeated measures.
CHAPTER IV

RESULTS AND DISCUSSION

Introduction

The ability to measure metabolic and respiratory function in human subjects during activity has been made easier due to advances in technology. The Aerosport KB1-C, developed by Aerosport, Inc. (Ann Arbor, MI), is a portable analyzer which measures, displays, and prints fractional concentrations of expired oxygen and carbon dioxide, as well as ventilation volumes. The metabolic data provided by this instrument were, until recently, available only from large metabolic measurement carts. With the invention of small portable metabolic measurement systems, such as the KB1-C, the physiological responses of activities that can be studied has been increased dramatically. The validity of the KB1-C has yet to be determined, so the purpose of this study was to determine the validity of a portable metabolic measurement system using the autocalibration feature.

Descriptive Characteristics of Subjects

The KB1-C was evaluated in the Human Performance Laboratory at the University of Wisconsin-LaCrosse. Twenty subjects, consisting of male and female volunteers from the University of Wisconsin-LaCrosse, agreed participate in this study. All subjects were active and familiar with the testing procedures. Descriptive characteristics of the 20 subjects are presented in Table 1.
Table 1. Descriptive Characteristics of Subjects (N = 20).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>23.2</td>
<td>2.39</td>
<td>19-27</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>173.3</td>
<td>8.20</td>
<td>157-191</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>70.9</td>
<td>12.22</td>
<td>56.2-95.2</td>
</tr>
</tbody>
</table>

Validation of QMC Ventilation Measurements

For this comparison, the subjects performed an exercise test on a treadmill which consisted of a standard warm-up of 3.5 mph and 10% grade, followed by three five minute workloads at a self-selected speed at inclines of 0, 2.5, and 5% grade. During this test, exhaled air was routed into the QMC and out the exhaust port into a Tissot spirometer during the final minute of each stage. Once the minute value was collected in the Tissot, the air was forced out the exhaust port of the Tissot spirometer and through the mouthpiece of the KB1-C.

Ventilation (VE) values measured by the KB1-C (STPD), QMC (BTPS), and Tissot spirometer (ATPS) were then converted to a standard volume (STPD) for purposes of comparison. It is important to note that the KB1-C provides VE values in STPD, rather than the standard of BTP. This is due to the KB1-C using its own internal temperature as the ambient temperature and correcting it to standard (0°C). Correction factors produced by the QMC were used for calculating the conversions to STPD. The
equations used by the QMC are presented in Appendix B. The VE values (STPD) measured by the KB1-C, QMC, and Tissot spirometer are presented in Table 2.

Table 2. Ventilation Volumes Obtained from the KB1-C, QMC, and Tissot Spirometer Corrected to STPD.

<table>
<thead>
<tr>
<th>Stage</th>
<th>QMC Mean</th>
<th>SD*</th>
<th>Tissot Mean</th>
<th>SD*</th>
<th>KB1-C Mean</th>
<th>SD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>40.3</td>
<td>7.5</td>
<td>39.8</td>
<td>8.1</td>
<td>35.9**</td>
<td>8.4</td>
</tr>
<tr>
<td>II</td>
<td>40.6</td>
<td>12.9</td>
<td>39.8</td>
<td>14.4</td>
<td>35.8**</td>
<td>13.1</td>
</tr>
<tr>
<td>III</td>
<td>46.8</td>
<td>15.9</td>
<td>46.7</td>
<td>17.0</td>
<td>41.7**</td>
<td>15.8</td>
</tr>
<tr>
<td>IV</td>
<td>55.0*</td>
<td>18.6</td>
<td>53.3</td>
<td>19.4</td>
<td>47.7**</td>
<td>18.0</td>
</tr>
<tr>
<td>Overall</td>
<td>45.7</td>
<td>13.7</td>
<td>44.9</td>
<td>15.0</td>
<td>41.4**</td>
<td>13.8</td>
</tr>
</tbody>
</table>

*a Standard Deviation  
* Significantly (p < 0.05) different from Tissot  
** Significantly (p < 0.05) different from Tissot and QMC

Using a 3 x 4 ANOVA with repeated measures, a significant (p < 0.05) interaction was found between ventilation volumes measured by the KB1-C, QMC, and Tissot spirometer, thus Tukey’s post-hoc test was used to test for pair-wise differences. It was found that a significant (p < 0.05) difference in VE existed between the KB1-C and the QMC, as well as between the KB1-C and Tissot spirometer, at all stages and overall with the KB1-C producing lower values of VE in both comparisons. No significant (p > 0.05) difference in VE was found between the QMC and Tissot spirometer at stages I, II, III, and overall, however, a significant (p < 0.05) difference was found between the QMC and Tissot spirometer at stage IV.
Pearson product moment correlations revealed a consistently higher correlation between the QMC and Tissot at each of the four stages than the KB1-C compared to the Tissot spirometer. These correlations are presented in Table 3.

Table 3. Correlation Between Tissot Spirometer vs QMC and Tissot Spirometer vs KB1-C.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>I</th>
<th>II</th>
<th>Stage III</th>
<th>IV</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tissot vs QMC</td>
<td>0.97*</td>
<td>0.99*</td>
<td>0.99*</td>
<td>1.00*</td>
<td>0.99*</td>
</tr>
<tr>
<td>Tissot vs KB1-C</td>
<td>0.81*</td>
<td>0.94*</td>
<td>0.94*</td>
<td>0.94*</td>
<td>0.99*</td>
</tr>
</tbody>
</table>

* Significant at p < 0.05

The Tissot spirometer was utilized to test the validity of the VE measures of the QMC. From this test the QMC was accurate up to VE values of $46.7 \text{ L.min}^{-1}$ STPD. At $53.3 \text{ L.min}^{-1}$, as measured by the Tissot, the QMC produced significantly (p < 0.05) lower measures of VE with a difference of $1.7 \text{ L.min}^{-1}$. Measures above $46.8 \text{ L.min}^{-1}$ from the QMC were statistically different, so measures in VE above this level cannot be used with confidence.

The KB1-C VE values, as compared to both the QMC and Tissot, were significantly (p < 0.05) lower at each stage and overall. From these data it is concluded that the VE measures by the KB1-C are inaccurate.
Comparison of Physiological Measures Between the KB1-C and QMC

For this comparison each of the subjects performed an exercise test on a treadmill, which consisted of a standard warm-up of 3.5 mph and 10% grade, followed by three workloads of a self-selected speed and inclines of 0, 2.5, and 5% grade. During this test, exhaled air was routed into the QMC and out the exhaust port through the mouthpiece of the KB1-C for gas analysis.

**VE (STPD)**

The VE values (STPD) measured by the KB1-C and QMC are presented in Table 4.

<table>
<thead>
<tr>
<th>Stage</th>
<th>QMC Mean</th>
<th>QMC SD*</th>
<th>KB1-C Mean</th>
<th>KB1-C SD*</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>41.8</td>
<td>7.0</td>
<td>40.7</td>
<td>6.5</td>
<td>1.1</td>
</tr>
<tr>
<td>II</td>
<td>45.4</td>
<td>12.4</td>
<td>44.7</td>
<td>13.1</td>
<td>0.7</td>
</tr>
<tr>
<td>III</td>
<td>52.0</td>
<td>15.0</td>
<td>52.4</td>
<td>15.8</td>
<td>-0.4</td>
</tr>
<tr>
<td>IV</td>
<td>62.2</td>
<td>18.8</td>
<td>62.8</td>
<td>20.7</td>
<td>-0.6</td>
</tr>
<tr>
<td>Overall</td>
<td>50.4</td>
<td>12.3</td>
<td>50.2</td>
<td>13.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

* Standard Deviation

Using a 2 x 4 ANOVA with repeated measures, no significant (p > 0.05) difference was found for VE between the KB1-C and QMC at any stage and overall. Pearson
product moment correlations reveal significant ($p < 0.01$) correlations of $r = .95, .97, .99, \text{ and } .99$, between instruments at stages I, II, III, IV, and overall, respectively.

The KB1-C measures of VE were not significantly ($p < 0.05$) different from those of the QMC at various levels of VE. These results are opposite to those obtained from the test directly comparing the VE values among the Tissot, QMC, and KB1-C, where the KB1-C values were significantly lower between the Tissot and QMC at all levels. This may be due to a methodological problem with the equipment arrangement during the test among the three machines. When the KB1-C was compared to the QMC, only half the readings of the KB1-C were higher for VE, while the other half were lower than the QMC. In the test to compare the Tissot, QMC, and KB1-C, the KB1-C greatly underestimated VE compared to the QMC at all levels. This may have been due to a leakage of air, an incomplete emptying of the Tissot, or a lack of bidirectional flow. The arrangement was chosen to allow the three machines to be tested in series, yet allow the KB1-C mouthpiece to have open flow through it. Any equipment (i.e., Hans-Rudolph valve, Tissot spirometer) attached to the end of the mouthpiece caused a rise in carbon dioxide values, due to a back pressure. This meant the air must be passed through the KB1-C mouthpiece in a unidirectional flow, which is not how the unit was meant to be used. The mouthpiece is usually at the mouth of the subject where both inhalations and exhalations pass. This study simulated only exhalations by emptying the Tissot through the KB1-C mouthpiece. Accordingly, it cannot be concluded that the KB1-C is inaccurate.
From this test true comparisons can only be made up to VE values of 46.8 L·min⁻¹ as measured by the QMC, due to the inaccuracy of the QMC above this value. However, due to the high correlation between the KB1-C and QMC, the measures may be used practically. This is similar to the findings of Wideman et al. (1996) and Novitsky et al. (1994) who found similar correlations of \( r = .96 \) and \( .95 \), respectively, with the Teem 100 and concluded that it may be used to accurately measure VE during exercise.

**\( F_{\text{E}O_2} \)**

The overall means, standard deviations, and differences between the two machines for fractional concentrations of expired oxygen (\( F_{\text{E}O_2} \)) are presented in Table 5.

<table>
<thead>
<tr>
<th>Stage</th>
<th>QMC Mean</th>
<th>SD*</th>
<th>KB1-C Mean</th>
<th>SD*</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.1600</td>
<td>0.0048</td>
<td>0.1622</td>
<td>0.0045</td>
<td>-0.0022</td>
</tr>
<tr>
<td>II</td>
<td>0.1619</td>
<td>0.0049</td>
<td>0.1642</td>
<td>0.0041</td>
<td>-0.0023</td>
</tr>
<tr>
<td>III</td>
<td>0.1609</td>
<td>0.0042</td>
<td>0.1637*</td>
<td>0.0037</td>
<td>-0.0028</td>
</tr>
<tr>
<td>IV</td>
<td>0.1626</td>
<td>0.0045</td>
<td>0.1649</td>
<td>0.0047</td>
<td>-0.0023</td>
</tr>
<tr>
<td>Overall</td>
<td>0.1613</td>
<td>0.0042</td>
<td>0.1637</td>
<td>0.0038</td>
<td>-0.0024</td>
</tr>
</tbody>
</table>

* Standard Deviation  * Significant at \( p < 0.05 \)

A significant (\( p < 0.05 \)) difference was found between the KB1-C and QMC for \( F_{\text{E}O_2} \) using a 2 x 4 ANOVA with repeated measures. The Tukey's post-hoc test revealed
a significant (p < 0.05) difference in FEO2 between the KB1-C and QMC at stage III. Although, the KB1-C consistently produced higher FEO2 values, no significant (p > 0.05) differences existed between the means at stage I, II, IV, and overall. Pearson product moment correlations reveal significant (p < 0.05) correlations at each stage r = .88, .87, .75, .87, and .85 for stage I, II, III, IV, and overall, respectively.

\[ \text{F}_{\text{E}}\text{CO}_2 \]

The overall means, standard deviations, and differences between the two machines for fractional concentrations of expired carbon dioxide (\( F_{\text{E}}\text{CO}_2 \)) are presented in Table 6.

Table 6. Comparison of F\( _{\text{E}}\text{CO}_2 \) Values Between the KB1-C and QMC According to Workload and Overall Measures.

<table>
<thead>
<tr>
<th>Stage</th>
<th>QMC Mean</th>
<th>QMC SD*</th>
<th>KB1-C Mean</th>
<th>KB1-C SD*</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.0477</td>
<td>0.0041</td>
<td>0.0461*</td>
<td>0.0038</td>
<td>-0.0016</td>
</tr>
<tr>
<td>II</td>
<td>0.0458</td>
<td>0.0050</td>
<td>0.0440*</td>
<td>0.0044</td>
<td>-0.0018</td>
</tr>
<tr>
<td>III</td>
<td>0.0469</td>
<td>0.0047</td>
<td>0.0451*</td>
<td>0.0040</td>
<td>-0.0018</td>
</tr>
<tr>
<td>IV</td>
<td>0.0467</td>
<td>0.0043</td>
<td>0.0452*</td>
<td>0.0041</td>
<td>-0.0015</td>
</tr>
<tr>
<td>Overall</td>
<td>0.0468</td>
<td>0.0043</td>
<td>0.0451*</td>
<td>0.0039</td>
<td>-0.0017</td>
</tr>
</tbody>
</table>

* Standard Deviation
* p < 0.05

The KB1-C consistently (p < 0.05) produced lower F\( _{\text{E}}\text{CO}_2 \) values, and the Tukey's post-hoc test indicated significant (p < 0.05) differences at all stages as well as overall.
Pearson product moment correlations reveal highly significant (p < 0.05) correlations of $r = .92, .92, .89, .94, .92$ for stage I, II, III, IV, and overall, respectively.

From these data it was concluded that the KB1-C accurately measures $F_{\text{E}O_2}$, but not $F_{\text{E}CO_2}$. Also, the differences in overall fractional gas concentrations of .0024 for oxygen and .0017 for carbon dioxide exceed the accuracy claims of $\pm .08\%$ and $\pm .05\%$ by the manufacturer, which equates to fractional concentrations of $\pm .0008$ and $\pm .0005$ for oxygen and carbon dioxide, respectively. It is important to note that the error in gas concentrations found may or may not be statistically significant, but the error remains consistent throughout the stages, especially $F_{\text{E}CO_2}$, which remains within a fractional concentration of .0003.

These findings are very similar to those of Wideman et al. (1996). They, too, concluded that the Teem 100, predecessor to the KB1-C, accurately measures $F_{\text{E}O_2}$, but not $F_{\text{E}CO_2}$. Their correlation of $r = .83$ was similar to that found in this study of $r = .85$ for $F_{\text{E}O_2}$. However, they found a moderate correlation between the Teem 100 and the Rayfield system of $r = .77$, where in this study a correlation of $r = .92$ was found between the KB1-C and QMC for $F_{\text{E}CO_2}$.

$V_{O_2}$

Oxygen consumption values obtained from the KB1-C and QMC were compared using a $2 \times 4$ ANOVA with repeated measures. The $V_{O_2}$ values obtained from the KB1-C were significantly (p < 0.05) lower than those from the QMC at each stage and overall. Pearson product moment correlations were significant (p < 0.05) for stages II, III, IV, and overall ($r = .97, .94, .96, and .96$, respectively). A nonsignificant (p > 0.05) correlation of
r = .22 was found for stage I. Absolute values of oxygen consumption (VO₂), standard deviation and percent error are presented in Table 7.

Table 7. Comparison of VO₂ Values Between the KB1-C and QMC According to Workload and Overall Measures.

<table>
<thead>
<tr>
<th>Stage</th>
<th>QMC Mean</th>
<th>SD*</th>
<th>KB1-C Mean</th>
<th>SD*</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2.0549</td>
<td>0.1037</td>
<td>1.9277</td>
<td>0.1244</td>
<td>6.19</td>
</tr>
<tr>
<td>II</td>
<td>2.1754</td>
<td>0.5888</td>
<td>2.0548*</td>
<td>0.6145</td>
<td>5.54</td>
</tr>
<tr>
<td>III</td>
<td>2.5368</td>
<td>0.6608</td>
<td>2.4149*</td>
<td>0.6941</td>
<td>4.81</td>
</tr>
<tr>
<td>IV</td>
<td>2.8627</td>
<td>0.7033</td>
<td>2.7609*</td>
<td>0.7915</td>
<td>3.56</td>
</tr>
<tr>
<td>Overall</td>
<td>2.4092</td>
<td>0.4931</td>
<td>2.2878*</td>
<td>0.5304</td>
<td>5.04</td>
</tr>
</tbody>
</table>

* Standard Deviation
* p < 0.05

From these data it was concluded that the KB1-C cannot be used to measure VO₂ with confidence, despite the strong correlation, since there were significant differences found between all comparisons of the KB1-C and QMC. It is important to note that this conclusion is drawn under the assumption that the QMC is a valid reference system. Similar results to this study were found with the Teem 100 by Wideman et al. (1996) who found that when broken down into categories based on absolute VO₂, significant (p < 0.05) differences were found between the means of the Teem 100 as compared to the Rayfield system. When combined into an overall data set, no significant differences existed and a correlation of r = .95 was found. However, they concluded that the Teem
100 could be utilized to assess VO₂ because the overall data were not significantly different and correlated well. Previously, Novitsky et al. (1994) also found that the Teem 100 could accurately assess VO₂ since overall data revealed no significant (p < 0.05) differences between the Teem 100 and the Sensormedics 2900, as well as when broken down into separate VO₂ levels. A strong correlation of \( r = 0.97 \) was also found between the two systems for VO₂.

**VCO₂**

Values of carbon dioxide production (VCO₂), standard deviations, and percent error are presented in Table 8.

Table 8. Comparison of VCO₂ Values Between the KB1-C and QMC According to Workload and Overall Measures.

<table>
<thead>
<tr>
<th>Stage</th>
<th>QMC Mean</th>
<th>SD</th>
<th>KB1-C Mean</th>
<th>SD</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.9795</td>
<td>0.3891</td>
<td>1.8625*</td>
<td>0.3504</td>
<td>5.91</td>
</tr>
<tr>
<td>II</td>
<td>2.0950</td>
<td>0.7043</td>
<td>1.9845*</td>
<td>0.6910</td>
<td>5.27</td>
</tr>
<tr>
<td>III</td>
<td>2.4535</td>
<td>0.8242</td>
<td>2.3765*</td>
<td>0.8064</td>
<td>3.14</td>
</tr>
<tr>
<td>IV</td>
<td>2.8945</td>
<td>0.9261</td>
<td>2.8290</td>
<td>0.9681</td>
<td>2.26</td>
</tr>
<tr>
<td>Overall</td>
<td>2.3556</td>
<td>0.6743</td>
<td>2.2631*</td>
<td>0.6645</td>
<td>3.93</td>
</tr>
</tbody>
</table>

* Standard Deviation
* p < 0.05

Carbon dioxide production values between the KB1-C and QMC were compared using a 2 x 4 ANOVA with repeated measures. A significant (p < 0.05) difference was
found between the VCO₂ values measured by the KB1-C and QMC. The Tukey's post-hoc test indicated that the KB1-C VCO₂ values were significantly (p < 0.05) lower for stage I, II, III, and overall, but not at stage IV (p > 0.05). Pearson product moment correlations revealed significant (p < 0.05) correlations of r = .95, .97, .97, .98, and .98 for stage I, II, III, IV, and overall, respectively.

It was concluded from these data that the KB1-C may possibly produce more valid VCO₂ data at higher workloads, but not at low to moderate workloads, thus the KB1-C does not accurately assess VCO₂. Wideman et al. (1996) found similar results with the Teem 100, where significant differences existed and an overall correlation of r = .97 was found. However, the Teem 100 overestimated VCO₂, while this study reveals that the KB1-C underestimated VCO₂.

RER

There were no significant (p > .05) differences between any of the RER values measured by the KB1-C and the QMC. Pearson product moment correlations revealed significant (p < .05) correlations of r = .80, .57, .73, .72, .74 for stages I, II, III, IV, and overall, respectively. The lack of significant difference and moderate correlations are likely due to the KB1-C consistently producing lower values for both VO₂ and VCO₂. Respiratory exchange ratio, as described earlier, is calculated by the ratio of VCO₂ to VO₂, so the ratios produced by both machines were similar even though the values of VCO₂ and VO₂ differed. Therefore, even though the RER values produced by the KB1-C were not significantly different, they cannot be assumed to be accurate. The respiratory
exchange ratio (RER) values, which are calculated by the ratio of VCO₂ to VO₂, are presented in Table 9.

Table 9. Comparison of RER Values Between the KB1-C and QMC According to Workload and Overall Measures.

<table>
<thead>
<tr>
<th>Stage</th>
<th>QMC</th>
<th>KB1-C</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD*</td>
<td>Mean</td>
</tr>
<tr>
<td>I</td>
<td>0.97</td>
<td>0.06</td>
<td>0.97</td>
</tr>
<tr>
<td>II</td>
<td>0.97</td>
<td>0.05</td>
<td>0.96</td>
</tr>
<tr>
<td>III</td>
<td>0.97</td>
<td>0.06</td>
<td>0.98</td>
</tr>
<tr>
<td>IV</td>
<td>1.01</td>
<td>0.06</td>
<td>1.02</td>
</tr>
<tr>
<td>Overall</td>
<td>0.98</td>
<td>0.05</td>
<td>0.98</td>
</tr>
</tbody>
</table>

* Standard Deviation
CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The primary purpose of this study was to determine if the KB1-C portable metabolic measurement system, developed by Aerosport, Inc. (Ann Arbor, MI), is an accurate system for measuring ventilation (VE), oxygen consumption (VO$_2$), carbon dioxide production (VCO$_2$), fractional concentrations of expired oxygen (F$_{E}O_2$), fractional concentrations of expired carbon dioxide (F$_{E}CO_2$), and respiratory exchange ratio (RER).

Twenty subjects consisting of male and female volunteers from the University of Wisconsin-LaCrosse participated in this study. Each subject performed two exercise tests on a treadmill consisting of a standard warm-up of 3.5mph and 10% grade followed by three workloads at a self-selected speed and inclines at 0, 2.5, and 5% grade. During one test simultaneous measures of VE, VO$_2$, VCO$_2$, F$_{E}O_2$, F$_{E}CO_2$, and RER were recorded from the Quinton metabolic measurement cart (QMC) and the KB1-C. During the other test measures of VE were recorded from the QMC, a 120 L Tissot spirometer, and the KB1-C.

The statistical analyses included means, standard deviations, and ranges for the physical characteristics of all subjects. Comparisons between the QMC and KB1-C for the physiological parameters were performed with a 2 x 4 ANOVA with repeated measures and Pearson product moment correlations. The level of significance was set at $p = 0.05$. 

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Conclusions

The QMC was not previously tested for validity, so measures of VE were tested in this study by comparing the QMC to a Tissot spirometer. However, measures of gas fractions by the QMC were not tested for validity in this study. Therefore, the following conclusions are based on the assumption that the QMC is a valid reference for measures of \( F_eO_2 \) and \( F_eCO_2 \).

When VE was compared between the KB1-C and the QMC, the KB1-C was found to provide accurate VE data up to \( 46.7 \text{ L-min}^{-1} \) (STPD). After this volume, comparisons could not be made, due to possible error in the reference system (QMC). However, due to a high correlation, it was concluded that the KB1-C could be used above this point to assess relative changes in VE, but not absolute values. Accurate measures of \( F_eO_2 \) were found, but not \( F_eCO_2 \). Also, the measures of \( F_tO_2 \) and \( F_tCO_2 \) fall outside the accuracy claim of the manufacturer. Oxygen consumption and \( VCO_2 \) data were both found to be inaccurate, which produced similar RER values as the reference system, but cannot be termed accurate due to the error in both \( VO_2 \) and \( VCO_2 \). It is concluded that the KB1-C should not be utilized using the autocalibration procedure in a research capacity, due to the significant level of inaccuracy in measurements provided by the unit.

Recommendations

The following recommendations are offered for future considerations:

1. Another validation study should be performed with a 300 L Tissot spirometer, which will allow greater VE measurements to be recorded.
2. A more accurate method of connecting the equipment for testing in series should be used in future validation studies.

3. A system previously validated for all measures should be used as the reference system in future validation studies (e.g. measurement of $F_{E}O_{2}$ and $F_{E}CO_{2}$ validated via the Scholander technique).

4. In future validation studies, rest, low, medium, and high workloads should be utilized to collect a greater range of data.

5. A more “life-like” testing methodology should be implemented in future validation studies with exhalations being measured directly from a human subject.
REFERENCES


APPENDIX A

INFORMED CONSENT FORM
A VALIDATION STUDY OF THE KB1-C PORTABLE
METABOLIC MEASUREMENT SYSTEM USING
THE AUTOCALIBRATION FEATURE

I, ________________________________, volunteer to be a subject in the research study to
determine the accuracy of the Aerosport KB1-C portable oxygen measurement system
compared to a standard gas analysis system. I understand that participation in this study
requires me to make two visits to the Human Performance Laboratory at the University of
Wisconsin-LaCrosse. During these visits I will perform a graded exercise test on a
treadmill. I will begin with a low speed and grade to serve as a warm-up. After this, the
grade will be reduced to zero and the speed increased to a comfortable walking/running
pace that I choose. Every five minutes the grade will be increased two and a half percent
until I complete three stages or until I can no longer continue. The speed and grade will
then be lowered and I will cool down until my heart rate stabilizes. During the run I will
wear a Polar heart rate monitor and my exhaled air will be collected by breathing through
a mouthpiece with a nose clip in place.

I consider myself to be in good health and to my knowledge I am not infected with a
contagious disease or have any limiting physical condition or disability, especially with
respect to my heart, that would preclude my participation in the tests described above.

I understand that during the exercise test I may become short of breath, dizzy, nauseous,
and/or experience leg fatigue. I understand that in rare instances there exists the
possibility of heart arrhythmia, heart attack, stroke, or death.

I understand that the data collected from this study will be kept in a locked file cabinet in
the office of the primary investigator, with access limited to those directly working on the
study. I also understand that the results may be published, however, I will be represented
by a number with no reference to my name.

I understand that any further questions or concerns I may contact any of the following
people conducting the study:

Brent Reichert         Matthew Williams         Nancy Butts, Ph.D.
(608)784-3703          (608)785-2981         (608)782-8235

I understand that participation in this study is purely voluntary, and that I may
discontinue participation at any time without penalty.

SIGNATURE OF SUBJECT ______________________ DATE
SIGNATURE OF WITNESS ______________________ DATE
APPENDIX B

METABOLIC CALCULATIONS
METABOLIC CALCULATIONS

Determining VO₂ by open circuit spirometry involves measuring ventilation (VE), fractional concentration of oxygen (F̄₂O₂), and fractional concentration of carbon dioxide (F̄eCO₂). From these measures carbon dioxide production (VCO₂) and respiratory exchange ratio (RER) can be determined. How these values are used to calculate VO₂ can differ from one metabolic measurement system to another. This is the case with the KB1-C and the QMC. The KB1-C calculates VO₂ as follows (Aerosport, 1994):

\[
VO₂ = VE \cdot [(\%N₂E \cdot 0.265) - \%O₂E]
\]

In which VO₂ = oxygen consumption (L·min⁻¹)
VE = expired flow (L·min⁻¹) at STPD
\%N₂E = the percent of nitrogen in expired gas
\%O₂E = the percent of oxygen in expired gas

\%N₂E is calculated as: \[[100 - (\%O₂E + \%CO₂E)]\]

In which \%CO₂E = the percent of carbon dioxide in expired gas

The QMC calculates VO₂ as follows (Jones, 1975):

\[
VO₂ = [1-(F̄eCO₂+F̄eO₂)/(1-F̄₁CO₂+F̄₁O₂)-F̄eO₂] \cdot VE
\]

In which VO₂ = oxygen consumption (L·min⁻¹)
F̄eCO₂ = the fractional concentration of carbon dioxide in expired gas
F̄eO₂ = the fractional concentration of oxygen in expired gas
F̄₁CO₂ = the fractional concentration of carbon dioxide in inspired gas
F̄₁O₂ = the fractional concentration of oxygen in inspired gas
VE = expired flow (L·min⁻¹) at STPD

The expired gas volume at BTPS conditions is calculated as follows (Jones, 1975):

\[
VE_{BTPS} = VE_{ATPS} \cdot (P_B - P_{H₂O}) \cdot 310/[(273 + T) \cdot (P_B - 47.07)]
\]

In which VE_{BTPS} = the volume of gas at BTPS
VE_{ATPS} = the volume of gas at ATPS
P_B = the barometric pressure in mmHg
P_{H₂O} = the partial pressure for gas that is 100% saturated with water vapor
T = the temperature at which the gas is measured (°C)
Since volumes of gases exchanged in metabolic measurements are expressed as the volume that gas would occupy at a standard temperature (0°C) and pressure (760 mmHg), and dry conditions (STPD), volumes expressed as BTPS are converted to a volume at STPD as follows:

\[ V_{E_{STPD}} = V_{E_{ATPS}} \frac{273}{273 + T} (P_B - P_{H_2O}/760) \]

From the same basic measurements carbon dioxide production, respiratory exchange ratio, and relative oxygen consumption can be determined (Aerosport, 1994):

\[ V_{CO_2} = V_{E_{STPD}} \cdot (F_eCO_2 - F_iCO_2), \text{ same for both the KB1-C and QMC} \]

\[ \text{RER} = \frac{V_{CO_2}}{V_{O_2}} \]

\[ V_{O_2} \, \text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} = (V_{O_2} \cdot 1000) / \text{subject's body weight (kg)} \]
APPENDIX C

OVERALL DATA CORRELATIONS
Figure 1. Relationship Between VE Measured by KB1-C and QMC ($r = .986$).
Figure 2. Relationship Between VE Measured by KB1-C and QMC (r = .987).
Figure 3. Relationship Between VE Measured by KB1-C and Tissot ($r = .996$).
Figure 4. Relationship Between VE Measured by QMC and Tissot (r = .992).
Figure 5. Relationship Between VO$_2$ Measured by KB1-C and QMC (r = .960).
Figure 6. Relationship Between $VCO_2$ Measured by KB1-C and QMC ($r = .976$).
Figure 7. Relationship Between RER Measured by KB1-C and QMC ($r = .738$).
Figure 8. Relationship Between $\text{FeO}_2$ Measured by KB1-C and QMC ($r = .853$).
Figure 9. Relationship Between $F_eCO_2$ Measured by KB1-C and QMC ($r = .920$).