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ASSESSING THE CPX EXPRESS RESPIRATORY GAS EXCHANGE SYSTEM USING MALE ATHLETES

by

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Chairperson

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The purpose of this study was to determine the accuracy of the Medical Graphics CPX EXPRESS system at oxygen consumption's exceeding 4.25 L/min using the traditional Douglas bag method as a reference. Twelve male subjects ages 19-37 (±5.25) years participated in two exercise sessions. The sessions were identical consisting of a max treadmill test with increases in both speed and grade. Each stage was three minutes in length followed by two minutes of low intensity walking during which gas analysis for the stage could be completed for both the manual and CPX systems. All subjects completed at least four stages of the protocol. Repeated ANOVA's were run for the first three stages for $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$ with the p-value adjusted for number of ANOVA's performed (p=0.05/3=0.0167). There were no significant differences between the systems for mean $\dot{V}_E$ or $\dot{V}O_2$ at any stage; however, mean $\dot{V}CO_2$ was higher for stages 1 and 2 by 3.8% and 3.0%, respectively. The CPX EXPRESS had previously been determined to accurately measure low to moderate exercise intensities. This study was primarily concerned with stages yielding $\dot{V}O_2$ values exceeding 4.25 L/min. Nine subjects completed stage 5 and four subjects completed stage 6. Separate MANOVA's were performed for stages 4, 5 and 6 using $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$ as the dependent variables. There were no significant interactions nor main effects for system or test time at any of these last three stages where $\dot{V}O_2$ averaged 4.34, 4.61, and 4.83 L/min, respectively. Results of this study suggest the CPX EXPRESS measures respiratory variables at higher intensities with acceptable accuracy.

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TABLE OF CONTENTS

Chapter

LIST OF TABLES

LIST OF FIGURE

CHAPTER I

REVIEW OF LITERATURE

Performance tests that measure maximal oxygen uptake ($\dot{V}O_{2\ max}$) are often used to predict an athlete's performance or determine an individual's aerobic endurance. Direct maximal tests are time consuming if done using a traditional bag method and expensive if done with an electronic breath-by-breath gas analysis system. The test protocol and equipment are usually determined by the circumstances of the test and desired accuracy of the results. Today, the classic Douglas bag method is often replaced by metabolic cart analyzers. The substantially higher price needs to be justified, and there is a need to determine the validity of the equipment to ensure that it accurately measures $\dot{V}O_{2\ max}$ for a wide range of individuals on the metabolic analyzers that have not yet been tested (12, 33). The greater initial expense of these systems may argue against their use in the general fitness setting where estimated $\dot{V}O_2$ measurements have been reported to be sufficient (1). Predicted tests are used for estimating $\dot{V}O_{2\ max}$ when exact values are not required.

Maximal oxygen uptake is the greatest amount of oxygen (O_2) a person can take in during physical work. The measurement is made at the mouth; however, it reflects the O_2 utilization by the cells, including the muscle cells performing the work of exercise (34). Maximal O_2 uptake is the maximal capacity to deliver and extract O_2 in the tissues of the

body at a particular state of fitness or physical training and is the most reliable method for estimating aerobic power and cardiorespiratory fitness (10, 19, 35). It consists of two factors: 1) maximal cardiac output (CO) and 2) arteriovenous O_2 difference (a-vO_2 diff) which is the peripheral extraction of delivered O_2 (27). The Fick equation relates CO and a-vO_2 diff as the circulatory system's ability to deliver and extract O_2 where:

$$\dot{V}O_2 = CO \times \text{a-v}O_2 \text{ diff}$$

Maximal CO is determined by maximal heart rate and stroke volume. The a-vO_2 diff is determined by the maximal O_2 content in arterial blood and the minimal O_2 content in mixed venous blood. If work rate is further increased and the maximal capacity to take in O_2 has reached its limit, there is no change in either $\dot{V}O_2$ or CO (19). Any increase in work rate after this point is accomplished anaerobically (1).

Neither the CO nor a-vO_2 diff are easily measured, so a more meaningful equation involves gas exchange. The following equation represents indirect use of O_2 where $\dot{V}O_2$ represents the difference between the rates at which O_2 is inspired and expired, $\dot{V}_I$ is the rate at which air is inspired, F_{IO2} is the fraction of O_2 in inspired air, $\dot{V}_E$ is the rate at which air is expired and F_{EO2} is the fraction of O_2 in expired air:

$$\dot{V}O_2 = (\dot{V}_I \times F_{IO2}) - (\dot{V}_E \times F_{EO2})$$

A volume measuring device determines $\dot{V}_E$, an O_2 analyzer measures F_{EO2} and room F_{IO2} air is assumed to be 20.93%.

The calculated values must also be converted from ambient temperature and pressure conditions saturated with water vapor (ATPS) to standard temperature and pressure dry conditions (STPD). The ambient barometric pressure (P_B) and the water

vapor pressure (WVP) recorded are at the gas temperature in Celsius (T_G) in the volume measuring device (1). The flow rates may be compared in environmental conditions that vary in altitude, heat and/or humidity. This is done using the following equation:

$$\dot{V}_E (STPD) = \dot{V}_E (ATPS) \times [(P_B - WVP)/760 \text{ mmHg}] \times [273 \text{ K}/(273 \text{ K} + T_G)]$$

Because nitrogen (N_2) is neither produced nor consumed during metabolism, the rate of N_2 production or consumption is assumed to be zero (1, 32, 36). Wilmore and Costill investigated the effect to which N_2 changes influence the accuracy of the calculation of $\dot{V}O_2$ via Haldane transformation during graded exercise tests of various intensities. Excellent agreement existed between the actual O_2 consumption values and those calculated using traditional Haldane transformation for their six subjects with the biggest difference between actual and estimated values being 230 ml or a 7.3% error (36). These results were verified in a study by Wagner et al. when 10 subjects each walked on a treadmill while two Tissot spirometers measured gas volumes (32). Metabolism was measured both with the closed-circuit method by directly measuring inspired and expired gases and with the open-circuit method based on collection of only expired gases. There was no significant difference between inspired and expired N_2 minute volumes and no difference between the two methods when calculating $\dot{V}O_2$. This supports the almost universal acceptance of N_2 equality in inspired and expired air. The fraction of N_2 in inspired air (F_{IN2}) is typically 79.04%. The fraction of N_2 in expired air (F_{EN2}) can be calculated from the following equation where F_{ECO2} is the fraction of CO_2 in expired air:

$$F_{EN2} = 1.00 - F_{EO2} - F_{ECO2}$$

The difference in N_2 concentration between inspired and expired air is the result of differences in the volumes. The F_{EN2} can be placed in the following equation:

$$\dot{V}_I=(\dot{V}_E \times F_{EN2})/F_{IN2}$$

The $\dot{V}O_2$ is determined by putting V_I into the original gas exchange equation:

$$\dot{V}O_2= (\dot{V}_I \times F_{IO2}) - (\dot{V}_E \times F_{EO2})$$

Oxygen uptake is, therefore, calculated based on the measurement of ventilation along with O_2 and CO_2 fractions.

VOLUME MEASUREMENT

Volume can be measured by gas meters, spirometers or by a flow rate using volume transducers. Dry gas meters are suitable for manual systems with intermittent collection of expired gases. Bags or balloons are most easily measured this way. The gas meters can be used directly in either inspired or expired sides of a breathing valve circuit. They are reasonably accurate if used with constant flow, but may be subject to mechanical leaks and maladjustment. The moisture in the expired gas is also a potential cause of error.

Spirometers such as the Tissot type water-sealed come in sizes of 120, 350 or 600 liter tanks. Their uses include measuring volumes collected into bags or balloons, calibrating other volume and flow devices and direct use in manually operated systems. They are advantageous because of their simplicity, accuracy and ease of quality control. Problems include size, difficulty connecting recording devices, and poor frequency

response and potential resistance to breathing when used as a direct measurement device (34).

Flow rate is measured by pneumotachographs. The most common devices consist of either a number of parallel tubes (Fleish) or a series of fine wire mesh screens. Both of these devices offer a small resistance to airflow. Any small pressure drop can be measured and then related to the amount of airflow. There is a linear relationship between gas flow and pressure drop. The linear coefficient is constant only during non-turbulent flow. Turbulence can be reduced if the gas is allowed to flow through a long, straight, smooth walled tube. Rapidly changing flow rates may not be measured accurately if the pneumotachograph is unable to respond instantaneously. A relatively new device called the turbine volume transducer uses a lightweight impeller to directly measure volume of gas flow, are linear over a wide range of flow rates, behave identically for different gas compositions and offer good frequency response characteristics. They are good for breath-by-breath analysis and can be used to measure bi-directional gas flow. The speed of the impeller, however, is sensitive to water or saliva deposition (34).

A water-sealed spirometer is recommended as a primary standard for volume measurements while spirometer volume change over a timed period can be used as a flow standard. Secondary standards include calibrated large volume syringes of 1-4 liters and various gas flow meters. If flow or volume signals are further processed by analog means, the results are subject to the response characteristics and calculation methods of these instruments as well.

The simplest method to calibrate a pneumotachograph is under identical conditions to the testing process. A known volume or flow of gas with its temperature, humidity and gas composition the same as the anticipated measured gas should be delivered to the pneumotachograph.

GAS ANALYZERS

Haldane and Scholander analyses of expired gases are time consuming yet accurate. They can be used to calibrate gas analyzers and to analyze stored gases used for calibration. The reliability of the Haldane gas analysis method has been shown to be within ±0.02% but can only handle samples up to 30% of either CO_2 or O_2 in a sample (6, 21, 25). Scholander analysis, developed in 1947, permits the determination of CO_2, O_2 and N_2 in 0.5 cc or less of respired gases with an accuracy of ±0.015 volume percent. This method proposed a drastic change in apparatus for measuring expired air by using an accurately calibrated micrometer as a measuring device. The analysis typically takes 6-8 minutes and uses samples containing from 0-99% absorbable gases (24).

Carbon dioxide analyzers measure absorption of CO_2 by characteristic wavelengths of infrared light. Light passes through a cell containing gas to be measured and the amount of light transmitted is compared to a known constant value. The absorption is proportional to the CO_2 fraction.

Oxygen analyzers are of two main types, the paramagnetic analyzer and the electrochemical analyzer. The first paramagnetic analyzer was developed by Pauling in 1946 and measured the partial pressure of O_2 in expired air. Since O_2 is strongly

paramagnetic in nature, the meter can analyze it very accurately even in the presence of other gases. The sample is uncontaminated as no other solutions or chemicals are used for analysis. The paramagnetic analyzer measures the change in a given magnetic field introduced by changes in O_2 quantity in a chamber located within the magnetic field. Shepard tested one such paramagnetic analyzer, the Beckman E-2. He found that it measures to within ±0.02% on the average (25). The average performance of this O_2 analyzer does not match the best that can be achieved by chemical analysis however. Because of its simplicity of operation, chemical analysis yields more consistent results and is preferable for routine work. The electrochemical O_2 analyzers depend on a chemical reaction between O_2 and a reusable substrate that results in the generation of an electrical current. The current is proportional to the quantity of O_2 molecules. Both devices measure partial pressure and they are affected by water vapor, pressure in sampling systems and changes in barometric pressure and altitude (34).

Both the CO_2 and O_2 analyzers report the O_2 and CO_2 fraction of the total gas. The gas analyzers should be checked for linearity within a range of needed values by analyzing gases of differing O_2 and CO_2 concentrations. A three point calibration for each CO_2 and O_2 in their respective analyzers (0% for both gases, 6% CO_2 and 15% O_2, and 3% CO_2 and 18% O_2) is suggested (10). Cunningham et al. described the accuracy of equipment used to measure $\dot{V}O_2$ finding that CO_2 and O_2 electronic gas analyzers show high levels of accuracy when calibration gases are used. The regression correlation coefficient for CO_2 was r=0.95 with a standard error of 0.19 L/min and for O_2 was r=0.99 with a standard error of 0.09 L/min (8).

RELIABILITY

The major source of variation in a measure is the response of the individual rather than an error in measurement. Henry found that measurement error variance is only 3-4% as large as intra-individual variance and has little influence on the reliability (9). Kannagi et al. found that the primary cause of variability was intra-individual variation rather than a significant difference in the accuracy of the methodology of the gas analysis (12).

The presence of differences in repeat $\dot{V}O_2$ values on the same individual does not establish the existence of experimental or technological errors. Technological errors include the instrument error, uncontrolled environmental error and other undetermined errors which are relatively constant rather than proportional to the magnitude of the absolute score (13). Katch et al. did a study on five subjects eight times to determine biological variation. The combined sources of error allowed for a variance of 5.6% and approximately 90% of this was due to biological variation and less than 10% due to technological error. Only 0.38% of the error in $\dot{V}O_{2\ max}$ calculation was attributed to instrumental error in the study suggesting that the greatest source of variation in $\dot{V}O_{2\ max}$ between individuals is accounted for by individual differences. The largest variability in $\dot{V}O_2$ can be attributed to the biological tendency of individual's responses to vary about a theoretical true score. The biological variation may be larger in untrained subjects than it is in trained subjects due to increased variation in both the transport and the extraction of the O_2 at the cellular level, but this is undetermined (13).

McArdle et al. found that there was a test-retest reliability coefficient (r=0.95) for $\dot{V}O_{2\ max}$ on a three minute step test (18). When Taylor tested the reliability of $\dot{V}O_{2\ max}$ by

determining the coefficient of reliability for 28 duplicate measurements, he found $\underline{r}$=0.95 with a standard error of 0.84 cc or 2.4%. Randomness accounted for 18.7% of the variation, 80.5% was due to differences between individuals and less than 1% due to day to day variability (29). Reybrouck found the percentage of difference of a test-retest to be 7.7 ± 3.2% (23).

VALIDITY

Validity of measurement indicates the degree to which an instrument measures what it is supposed to measure (30). For a system to be valid, it must first be reliable (16). The validity of a breath-by-breath system is best tested using simultaneous comparison with the Douglas bag method as a reference (22, 23). Correlation coefficients higher than $\underline{r}$=0.98 have been reported between such systems. The means of two simultaneous measurements are considered to be the best estimate of the true mean value and the limits of agreement may give an estimate of the agreement between the two (23).

OXYGEN UPTAKE SYSTEMS

Oxygen uptake can be measured manually, semi-automatically or automatically. The Douglas bag method using a spirometer such as the Tissot tank is the classic manual method for determination of $\dot{V}O_2$. Subjects breathe through a breathing valve from which expired air is collected in a meteorological balloon or directly into a Tissot. Timed collections of mixed expired gases are made at intervals during expiration. A series of bags can be connected to stopcocks for sequential sampling if desired. Following gas

collection, the bags are emptied into a spirometer or through a gas meter to determine volume. Mixed, expired CO_2 and O_2 fractions can be determined using appropriate analyzers. Water vapor is often removed first as speed is not crucial.

The Tissot method is advantageous as it is accurate to ±2% (10). It is ideal for exercising under steady state conditions; thus, manual systems are most often used during constant work rate exercise testing. The disadvantages of using a Tissot are that it is time consuming, the subject is somewhat hampered by the equipment limiting the ability to move freely, and it only provides an average $\dot{V}O_2$ during the collection period.

Sources of error for a manual system include the meteorological balloons being slightly permeable for O_2 and CO_2 although the diffusion has been found to be less than 0.1 percent over two hours (23, 31). Diffusion would overestimate $\dot{V}O_2$ and underestimate $\dot{V}CO_2$ measured with the Douglas bag. Incomplete emptying of the bags can also lead to underestimation of $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$. The flow meter used can contribute to error in manual measurement as can the timing of the collection period for the system (23). Commercially available gas mixtures used to standardize electronic gas analyzers are often accepted without validation leading to systematic error in $\dot{V}O_2$ measurement. A collection period of 60 seconds is recommended as shorter collection periods multiply the calculation equation errors. Barometric pressure, T_G and WVP of the gas affect the calculation accuracy; however, they have little effect on measurement error (10). Accurate determination of $\dot{V}O_2$ in the classic Douglas bag approach therefore, depends mainly on reliable measurement of the gas flow and expired gas fractions.

In semi-automatic measurement, air is drawn in through a one-way mouthpiece valve. On expiration, air is blown out through the mixing chamber past a thermometer, and through a volume measuring device. A mixed gas sample for analysis is drawn off through a sampling port on the mixing chamber by a vacuum pump and passes through a valve into a collecting bag (1). The volume of air expired is measured in a balanced spirometer such as the Tissot and the mixed expired gas fractions of F_{EO2} and F_{ECO2} are passed through a desiccant to dry them and then analyzed with the Haldane or Scholander techniques or by electronic gas analyzers. Gas temperature at the volume measuring device and the P_B are recorded to correct for water pressure in the expired gas in relation to the gas used for calibration (2).

Wilmore and Costill tested a semi-automated system of respiratory and metabolic data during exercise testing in 1974. Traditional methods at this time required up to several hours of time just for simple data acquisition and reduction. Systems were being developed which gave immediate, on-line data acquisition, reduction and display on a breath-by-breath basis. However, many of these systems were not practical for field settings or in places where computer terminals were not available. Semi-automated systems were the answer to this problem plus they had the added features of portability and relatively low cost. The system tested by Wilmore and Costill had electronic gas analyzers, pneumotachometers, speed, accuracy and an approximation of real-time data reduction which were features of the computerized versions. The results showed it was possible to have data completely reduced and displayed within 10 seconds following the end of that collection period. This equipment was advantageous over manual

measurement as the calculated values could be seen to determine if the system was functioning properly and it provided an additional check on the subject's status during the test (37). However, Balikian et al. found that this system was not valid for $\dot{V}O_2$ non-steady state testing (3).

Poole et al. studied a simple and convenient semi-automated system for respiratory gas exchange. The total error of the continuous flow sampling (CFS) system was determined by comparing it with the classical bag collection method followed by gas analysis. Six subjects submaximally cycled on a Monark bicycle ergometer with measurements taken after four minutes of continuous exercise at steady state as shown by a plateau in $\dot{V}_E$. Gas was collected in neoprene bags concurrently with continuous sampling from the mixing chamber using rotating valves to deliver gas to one of three collection bags. The other two bags were analyzed simultaneously. Ventilation could be determined by a gasmeter or pneumotagraph in series with the collection bags. Thus, sequential samples could be automatically obtained and analyzed. The absolute values of O_2 and CO_2 concentrations from the bags were used as criteria to determine the validity of the CFS (21).

The gas collected in the bags was also analyzed directly by electronic analyzers revealing varying degrees of reliability when compared to Scholander analysis of the same bags. The CFS system is limiting in that mean expired gas concentrations from the continuous on-line gas analysis are calculated by selecting an average value from the strip-chart recordings during each minute of continuous sampling. Therefore, errors occur in unsteady state conditions such as hyperventilation during severe exercise. The

possible absolute error of $\dot{V}O_2$ with the system rose with increasing work rate and $\dot{V}_E$ levels. The CFS can be used with accuracy at moderate steady state intensities; however, the traditional Douglas bag method should be used for maximal intensities (a $\dot{V}_E$ of about 140 L/min) as $\dot{V}O_2$ error approached ±0.49 L/min in 95% of the cases. This system should not be used if $\dot{V}_E$ is not constant to within ±0.3 L/min (21).

In clinical settings, collection of gases using the traditional Douglas bag method is not practical. Many laboratories now use electronic gas analyzers to save time. Microprocessor based automated systems theory and operation are analogous to manual collection. Volume is measured in a volume measuring device while gas fractions are measured in electronic gas analyzers. On-line collection and analysis speed up $\dot{V}O_2$ measurement and make breath-by-breath measurement possible allowing for the analysis of respiratory variables during the non-steady state phase of exercise (22, 23). An advantage for systems measuring both inspiratory and expiratory flow is that correction is made for breath-by-breath changes in the functional residual capacity and the fluctuations in $\dot{V}O_2$ are smaller (4). When only expired gases are measured, the method calculates gas transport at the mouth associated with the quantity of gas actually expired which does not necessarily reflect the quantity of gas inspired in that breath. However, data show that when a number of breaths are compiled, the expiratory flow method can give accurate and reproducible measurement of cardiorespiratory gas exchange variables (4, 23, 26).

The accuracy of breath-by-breath systems is dependent upon the error present in the measurement of expired gas flow. Fluctuations in gas composition, water vapor and temperature during expiration result in flowmeter errors during expiratory flow when the

flowmeter is calibrated for a given ambient inspiratory gas. By including the analysis of N_2 flow in and out of the lung, breath-by-breath errors can be diminished. There is an inspiratory air flow error that is minimal if the apparatus dead space is small compared to the inspiratory volume (28). The best way to measure breath-by-breath is to compensate for changes in lung volume, yielding a minimal variation.

A Fleish pneumotachometer which is sensitive to gas composition variation and temperature change has been used in the past for breath-by-breath system flows. A Turbine flowmeter which has low dead space and lightweight assembly also has been tested as a volume measuring device. Yeh et al. used a Hans-Rudolph two-way valve so the flow meters measured the flow signals simultaneously during the test at varying flow rates for both the Fleish pneumotachometer and the Turbine flowmeter. The results showed that the volume measurements for both devices were within 4% accuracy. The Fleish pneumotachometer was within 5% for $\dot{V}O_2$ and $\dot{V}CO_2$ at rest, 100 Watts and 175 Watts. The turbine flowmeter errors were as large as 15% at rest, but as the work loads increased, the $\dot{V}O_2$ and $\dot{V}CO_2$ errors decreased (39).

The turbine flow signal lagged behind the Fleish signal at the start of inspiration or expiration demonstrating that the turbine may not sense the flow signals. At the end of expiration, the turbine flow signals did not return to zero giving a spin-after-stop effect. Those two problems were considered an alignment problem of matching the gas concentration signals to flow signals. If flow measurement lags behind the actual signal at the beginning of the inspiration, the computer will not be able to subtract all the CO_2 coming from the dead space forming this time lag resulting in a larger than actual $\dot{V}CO_2$.

These effects can be explained by the friction and inertia of the turbine. At high loads, these are decreased due to friction being overcome more quickly with a faster flow and a decreased time between end of expiration and start of inspiration causing a rapid change of direction for the turbine propeller. A "variable delay time" which adjusts the gas delay time according to the flow rate may compensate for these errors.

Calibration begins when the flow channel is calibrated by passing a known volume of air through the pneumotachograph using a standard syringe. The gas partial pressure input signals occur delayed in time with respect to the flow signal by the time required to transport the sampled air from the mouthpiece to the sensors. During the calibration procedure this delay is determined and introduced into the program (5). The gas transport delay times are found by connecting the gas sampling tubes to the output port of a valve which switches between two inputs connected to two different gas mixtures. The O_2 analyzer measures the difference in O_2 partial pressure between the sample and reference gases (34). The computer program calibrates gases by introducing known gas concentrations of the calibration and references gases. The gas concentrations and the flow are appropriately in phase and can be integrated at each sample interval to give $\dot{V}O_2$ and $\dot{V}CO_2$ for each breath as simultaneously air flow or volume are measured from the actual gas fractions (5, 15). Correction factors for respiratory exchange ratio (RER), water vapor and breathing valve dead space are applied by the computer breath-by-breath (5).

The sampling gas line connects directly to the mouth piece and a mixing chamber, which is likely to be inaccurate during rapid changes in ventilation, is unnecessary so this

is advantageous for breath-by-breath systems (26). Additionally, work rate protocols of as short as one minute can be used with these rapid analyzing systems. The greatest disadvantage of these systems is their initial expense (22).

The application of automated computer systems has increased accuracy and reduced the time to complete the test using fewer technicians during the test procedure. Wilmore et al. conducted a study establishing the validity of the Beckman Metabolic Measurement Cart (MMC). A turbine sensed expired air volume by generating pulses as the gas flows over a high velocity volume transducer. A constant aliquot of the expired air was drawn from a mixing chamber into a Beckman OM-11 O_2 analyzer and a Beckman LB-2 CO_2 analyzer and then returned to the mixing chamber prior to the gas passing through the volume transducer. The MMC was evaluated against another automated computer system and a semi-automated system both of which had been previously determined accurate. There was no significant difference in F_{EO2} and F_{ECO2} between the systems, however a significant difference in $\dot{V}_E$ was found at lowest metabolic load between MMC and the other computer system. Statistically significant differences were found for $\dot{V}O_2$ between MMC and the other computer system, however there were no significant differences in $\dot{V}O_2$ between the MMC and the semi-automatic system (38).

Additional studies compared the MMC Horizon to the Douglas bag method. Versteeg and Kippersluis found that $\dot{V}O_2$ values measured with the MMC were higher than those of the conventional Douglas bag method although there was not a significant difference in $\dot{V}O_{2\ max}$ (31). Matthews discovered $\dot{V}O_2$ values on the Horizon system were

consistently lower than the breath-by-breath and non-automated systems although the differences were not significant during steady state exercise. During non-steady state exercise, there were significant differences at higher work loads between the breath-by-breath and the Horizon systems (17). Jones conducted a study on the Horizon system and found high precision when compared to the Douglas bag's with a $\underline{r}$=0.99 during steady state exercise and a $\underline{r}$=0.99 during incremental exercise. When compared to a breath-by-breath system, there was not a significant difference between the two systems with a $\underline{r}$=0.95 (11). Kannagi et al. found the reliability for the manual bags was $\underline{r}$=0.98 for $\dot{V}_E$ and $\underline{r}$=0.99 for $\dot{V}O_2$ and $\dot{V}CO_2$ between the two tests while for the MMC it was $\underline{r}$=0.99 for $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$ (12).

Reybrouck studied 21 pediatric cardiac patients each exercising on a treadmill. The speed of the treadmill was 4.8 or 5.6 km/h depending on the child's age with the inclination varying from 0-6%. Expired air flow, F_{EO2} and F_{ECO2} were consistently sampled at the mouthpiece. For validation purposes, the expired air leaving the Fleish pneumotachograph was collected simultaneously in a Douglas bag for one minute periods. The concentrations of O_2 and CO_2 in the bags were determined with an infrared CO_2 analyzer and a paramagnetic O_2 analyzer. No significant differences were found between any of the respiratory variables between the mean values calculated by the breath-by-breath system and those obtained by the Douglas bag method suggesting the system was valid. Three tests were done over a two day period to test reliability and no significant differences were found for the mean values of heart rate, $\dot{V}_E$, $\dot{V}O_2$, $\dot{V}CO_2$ or RER (23).

The newest technology in the $\dot{V}O_2$ field involves portable telemetry systems. Field tests during a sporting activity allow the energy costs of physical movement to be measured during the actual activity by reducing the monitoring apparatus in size and mass so the subject can exercise freely (14). Signals are transmitted via telemetry from a lightweight unit worn by the subject to a receiver unit. Subjects wear a face mask with a turbine flowmeter attached instead of the traditional mouthpiece and noseclip (7, 20). The flowmeter measures the rate of airflow, calculates $\dot{V}_E$ and counts the number of expiratory cycles per minute. To measure the concentration of O_2, expired air moves through a capillary tube to the transmitter unit that contains an O_2 analyzer with a polargraphic electrode. Signals from the portable unit are transmitted to the receiver unit. The receiver processes these data and displays and prints the results. One such system, the K2, is an electrochemical gas analyzer which uses a polargraphic electrode. The telemetric system does not contain a CO_2 analyzer so the calculation of $\dot{V}O_2$ assumes that the $\dot{V}_I$ is equal to $\dot{V}_E$.

Separate studies have been done on the K2 Cosmed Instrument to test reliability and validity resulting in mixed conclusions. Kawakami et al. checked the reliability of the Cosmed K2 system and the feasibility of its application in actual sport in 1992. Expired air was collected from eight subjects each exercising on a cycle ergometer. All were expiring air through the K2 mask and turbine into a Douglas bag. The expired air was passed through a Max Planck Gasmeter flow meter and gas concentration analyzer to calculate $\dot{V}_E$ and $\dot{V}O_2$. Flow volume measurements were shown to be highly reproducible with a r=0.99 between the first and second measurements with an error of -0.89% to

0.72%. This indicated that the flow volume measurements were in agreement with the actual flow from the syringe. Comparison of the K2 and the Douglas bag methods showed no significant differences in $\dot{V}_{E\,max}$ up to 180 L/min or in $\dot{V}O_{2\,max}$ at a $p< 0.05$ as the mean $\dot{V}O_2$ for the K2 systems was 3.0 ± 0.5 L/min compared to the Douglas bag value of 3.2 ± 0.5 L/min. The $\dot{V}O_2$ measurements were significantly higher for K2 than for the Douglas bag at the same points in this study; however, this was most likely due to methodological errors occurring during gas collection. Even with the $\dot{V}O_2$ discrepancies, the authors concluded that the system can be used for measuring physical fitness of players and confirming the effects of training (14).

A second study was done by Peel and Utsey to determine the effect of calculating $\dot{V}O_2$ assuming that RER=1.0 and to determine the effect of adjusting K2 values using a mathematical formula to adjust $\dot{V}O_2$ values using predicted RER values recommended by the manufacturer. The K2 was compared to a Gould 9000PC computerized metabolic measurement system with a paramagnetic gas analyzer working on the principle that different concentrations of O_2 will alter the magnetic forces acting on a test body. Ten subjects each walked at 3.0 mph and 0%, 5%, 10% and 15% grades. At each work level, subjects walked for four minutes with one of the $\dot{V}O_2$ systems in place. The treadmill was stopped after four minutes and the other gas collection system was put in place for another four minutes at the same intensity level. The second system was then the first system for the next intensity level. Data were averaged for the fourth minute of exercise to use in analysis. No significant differences in $\dot{V}_E$ between the two systems were evident ($p<0.0009$). Calculating $\dot{V}O_2$ without using a percent of CO_2 in expired air did not

significantly affect the results of the K2 system showing that assuming RER=1.0 is accurate enough for most $\dot{V}O_2$ measurements. Peel and Utsey found significantly lower $\dot{V}O_2$ values ($p<0.0002$) with the K2 system than with the computerized metabolic measurement system with the absolute difference increasing from rest to exercise. Peel et al. concluded that the lower $\dot{V}O_2$ values using the K2 system result primarily from differences in the methods of collecting and analyzing expired air, like the calibration of the O_2 sensor for the K2 using room air only, while calibration for the metabolic measurement system is performed with both room air and air that contains zero percent O_2 rather than from the method of calculating $\dot{V}O_2$. This study was limiting as it did not contain high levels of intensity (20).

Lucia et al. tested the reliability and validity of the system at submaximal and maximal exercise intensities. Randomly, $\dot{V}O_2$ was determined one day with the Douglas bag method and on two other days with the K2 system. The subjects completed six submaximal three minute stages on a treadmill. The subjects rested for five minutes and then completed a maximal test which consisted of one minutes stages to fatigue. During the last minute of each submaximal stage and during each maximal stage, the averages for $\dot{V}_E$, $F_EO_2\%$, and $\dot{V}O_2$ were recorded. No significant differences ($p>0.05$) in $\dot{V}_E$ were found and the correlation coefficients were consistently above $r=0.90$ for any intensity at ($p<0.01$). The percent variation in $\dot{V}O_2$ means between the three testing sessions was below five percent. The correlation's were high, always above $r=0.86$ ($p<0.01$). The K2 Cosmed system was determined to be reliable and valid in laboratory exercise testing (15). The assumption of a constant RER=1.00 did not lead to a significant lack of

accuracy in $\dot{V}O_2$ measurement. A drawback of the study and the others previously done was that measurements of $\dot{V}O_2$ could not be done on the Douglas bag and the K2 system simultaneously (16).

Crandall, Taylor and Raven had 15 subjects each undergo two graded exercise tests, one with the K2 system and one with a breath-by-breath system. The study indicated that the K2 system gas analyzer needs to be warmed up 60 minutes prior to exercise to prevent significant O_2 drift. Also, the exercise test duration must be less than 20 minutes to prevent O_2 drift. At low workloads, the K2 underestimated $\dot{V}O_2$ as Peel found, and at high work rates, the K2 overestimated $\dot{V}O_2$ as Kawakami found. These differences were never significant, confirming Lucia's results. Ventilation volumes were significantly larger ($p<0.03$) with the K2 device than the breath-by-breath system probably due to differences in external dead space using the face mask instead of mouth piece. The differences between the Douglas bag and K2 systems can be reduced with a correction factor when the actual RER is known. Crandall et al. concluded that the accuracy of the K2 system is determined by the duration of the warm-up and the length of the total test (7).

Cardiopulmonary exercise testing (CPX) directly measures $\dot{V}O_2$ and estimates anaerobic threshold using a V-slope technique to define a patients cardiovascular reserve and fitness level. The Medical Graphics CPX EXPRESS system is less complex than the CPX/D, is less expensive, more compact and yet said to maintain the same accuracy as the larger system. It is marketed towards clinical testing on site by physicians as a rapid way to get results and meet the needs of a diverse patient practice. Walschlager et al.

conducted an initial study of the CPX EXPRESS and CPX/D systems. The purpose was to check the validity of assessing $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ using the CPX EXPRESS and CPX/D automated respiratory gas analysis systems in comparison to the Douglas bag method. Subjects were 15 well trained male cyclists and/or runners with $\dot{V}O_{2\,max}$ values ranging from 2.9-4.76 L/min. Each subject completed a maximal exercise test on a treadmill or mounted bicycle with gases being collected 4-6 times throughout the test for 30 second intervals. The protocol consisted of two, five minute stages at steady state before incremental increases in work rate to maximal levels. Each subject indicated when he was approximately one minute away from fatigue and data were taken for 30 seconds to represent maximal exercise levels (33).

The CPX EXPRESS and CPX/D systems analyzed expired air minute by minute to correspond with the bag collection system. The O_2 concentration was measured with a Beckman OM-11 O_2 analyzer and the CO_2 concentration was measured with a Beckman LB-2 Medical gas analyzer. Haldane transformation was used to calculate the volume of inspired air from the expired gas volume. Calibration gases were certified standard gases verified by Haldane chemical analysis. Walschlager et al. found that the CPX EXPRESS and CPX/D systems were valid and had a high degree of accuracy when compared to traditional methods of analyzing metabolic and respiratory function at rest and during exercise. Fractions of O_2 and CO_2 concentrations along with $\dot{V}_E$ were used to determine VO_2 (ml/min), VCO_2 (ml/min) and V_E (L/min). The percent differences between each Medical Graphics system and the traditional system are shown in Table 1 (33).

Table 1

Mean ± (SD) Gas and Ventilation Values for the Douglas Bag and Two Medical Graphics Systems

	VO_2 (ml/min)	VCO_2 (ml/min)	V_E (L/min)
Douglas Bag	2392.2 ± 130.3	2542.7 ± 155.4	77.1 ± 4.7
CPX EXPRESS	2446.2 ±134.2	2417.6 ± 149.0	72.5 ± 4.5
% difference	2.2	4.9	5.9
r	0.95	0.99	0.99
CPX/D	2484.9 ± 130.4	2475.4 ± 146.2	73.1 ± 4.3
% difference	3.9	2.6	5.2
r	0.99	0.99	0.99

Several new systems have attempted to make the technology of open-circuit spirometry available for a variety of situations. They may be portable or less bulky, less expensive, and produce more rapid breath-by-breath results. One would be the K2 system and another is a scaled down version (aka) CPX EXPRESS. Each time such a system comes on the market, it is important that it be tested to make sure that it accurately measures respiratory variables over a wide range of aerobic capacities. Validity and accuracy studies are most often done using the manual bag method as the gold standard. Studies that have found significant differences between the breath-by-breath system's $\dot{V}O_2$ values and manual bag system's values have had a 4% or less difference between the two (12, 33) though most studies have shown no statistical differences between the two types of systems (11, 17, 23, 31). The Medical Graphics Corporation's CPX EXPRESS has been tested at $\dot{V}O_2$ values varying from 2.90-4.76 L/min and was found to be within a

2.2% difference through this range; however, to be useful for testing athletic populations, it should be validated at higher $\dot{V}O_2$ values as well (33).

CHAPTER II

METHODOLOGY

The purpose of this study was to validate the Medical Graphics CPX EXPRESS system using the traditional Douglas bag method as a reference.

SUBJECTS

Endurance athletes (N=12) between the ages of 19-37 years with $\dot{V}O_{2\ max}$ values ranging from 4.32-5.18 L/min participated in this study after reading and signing an informed consent and a Participation Activity Readiness Questionnaire (PAR-Q) from Appendix B. Descriptive data of the subjects are presented in Table 2. Subjects reported to the Human Performance Laboratory at St. Cloud State University for testing two separate times. Test procedures were repeated at a later date in order to compare results between trials for reliability purposes.

INSTRUMENTATION

For manual analysis, O_2 concentration was measured using an Ametek Applied Electrochemistry zirconia based fuel cell O_2 analyzer (S-3A). Carbon dioxide (CO_2) was analyzed using an Ametek Applied Electrochemistry infrared sensor CO_2 analyzer (CD-3A). The volume of the air in the 120 L neoprene bag was measured with a 350 L

Table 2

Subject Descriptive Data

Subject	Age (years)	Height (inches)	Weight (lbs.)
1	37	73.0	170.13
2	21	71.8	199.00
3	22	73.0	172.00
4	31	68.0	168.00
5	22	69.0	178.75
6	22	73.0	163.00
7	24	74.0	189.00
8	30	74.0	186.25
9	24	70.5	200.00
10	22	73.0	157.00
11	22	70.0	151.50
12	19	73.0	151.50

Collins Tissot Spirometer Gasometer and adjusted for the volume removed by the manual gas analysis. Haldane Transformation was used to calculate $\dot{V}_I$ from $\dot{V}_E$. The Medical Graphics CPX EXPRESS was used for computerized analysis and the corresponding reference (21% O_2) and calibration (12% O_2 and 5% CO_2) gases were used for both the manual and EXPRESS calibrations. The controlled slide valve (Desktop Diagnostics/CPX) from the Medical Graphics Corporation allowed for simultaneous measurement of O_2 uptake for both the manual and EXPRESS methods.

PILOT TESTING

Following Institution Review Board approval, several weeks of pilot testing various aspects of both the manual bag and EXPRESS systems was conducted.

Tissot Tank

The first step was to determine whether the Tissot correction factor for the tank was accurate. A 3.0 L Hans Rudolph calibration syringe was used as the standard to put air into the Tissot. The Tissot valve was closed after each air influx to prevent the bell from moving upward between 3.0 L injections. The Tissot scale was read after each inserted volume and the numbers were converted to volumes using the labeled bell factor of 324.4 cc/mm. Trials were done once a day for six days. The Tissot was found to read approximately 2.1% high on average for injected volumes of 70-100 L (See Figure 1 and Appendix C).

Data in the 70-100 L range were used as this is the approximate volume the bag would contain during testing. The Hans Rudolph syringe was thus the calibrating device for both the bag system and the EXPRESS. The same experiment was conducted using two Hans Rudolph one way valves in series into the Tissot so that the Tissot valve would not have to be opened and closed after each influx. The Tissot read higher in this manner which may have been due to excess air entering the bell through the reed valves because of the bell momentum at the end of each 3.0 L injection.

When the Tissot was filled with air, the difference between the volume of air injected with the syringe and that the Tissot showed was a consistent 2.1% difference between the two systems throughout the working range. To adjust for this consistent 2.1% overestimation of volume, the bell factor was corrected from 3.24 to 3.18 L/mm.

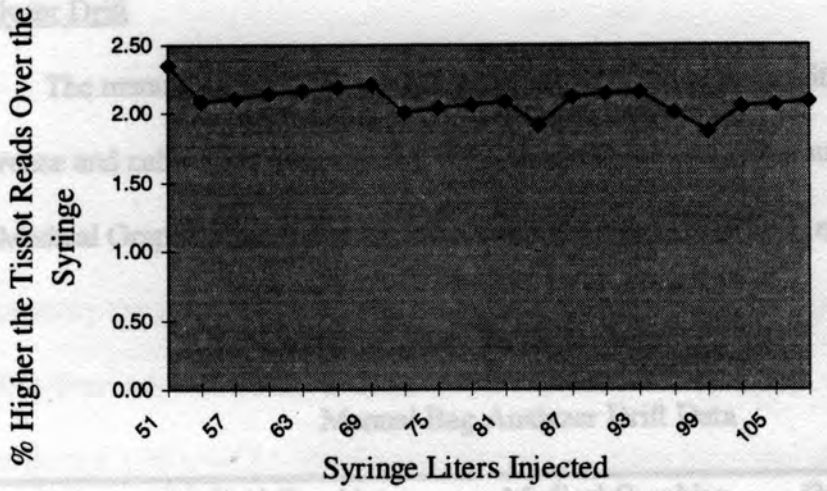

Figure 1

Percent Difference Between the Tissot and a 3.0 L Syringe

Calibration Techniques

The second area of pilot testing involved practicing calibration techniques for both the manual bag system and EXPRESS. The Applied Electrochemistry analyzers were warmed for 30 minutes in order to be stable. They were calibrated using both the calibration gas and reference gas also used by the EXPRESS system. The EXPRESS system analyzers were warmed up for 30 minutes, the pump was warmed up for 10 minutes and the system was then ready for use as instructed in the user's manual. Sensors in the EXPRESS measure the environmental conditions, automatically flush the gas lines and then sample the reference gas and calibration gas. The tester is only responsible for calibrating the pneumotach for volume using a 3.0 L calibrated Hans Rudolph syringe before beginning testing.

Analyzer Drift

The manual O_2 and CO_2 analyzers were calibrated initially with Medical Graphics reference and calibration gases. They were checked one and two hours later for drift with the Medical Graphics gases and a GenEx calibration gas (17.0% O_2 and 4.0% CO_2).

Table 3

Manual Bag Analyzer Drift Data

Time (hrs)	Medical Graphics Reference Gas		Medical Graphics Calibration Gas		Gen Ex Calibration Gas	
	% O_2	% CO_2	% O_2	% CO_2	% O_2	% CO_2
0	21.00	0.00	12.00	5.00		
1	20.97	0.00	11.98	4.99	16.89	4.00
2	20.98	0.00	11.96	4.99	16.88	4.00

Flow Rate

The flow rate for the manual bag system was measured both before and after a test using a 7.5 L Collins spirometer to check for any drift that might occur. The change from pre to post testing was found to be an average of 13.5 ml/min over five practice tests, an average difference of approximately 7%.

Table 4

Flow Rate Changes from Pre to Post Testing

Pre-Test (ml/mm)	Post-Test (ml/mm)
207.3	207.3
191.8	207.3
228.0	207.3
217.7	196.9
217.7	207.3

Test Protocol

A protocol for collecting expired gases was then piloted. Testing began with a slow walking stage to obtain low intensity data. Stages then consisted of a 5% grade increase at a constant speed of 2.68 m/s (6.0 mph) after stage one. After having two runners try the protocol, it seemed that they were stopping due to local fatigue in the legs before heart rates had reached estimated maximums. The protocol was then modified to consist of a 1.56 m/s (3.5 mph) stage followed by grade increases of 5% per stage at 2.68 m/s for the next two stages. The remaining stages were kept at a 10% grade while increasing speed 0.45 m/s (1.0 mph) each stage until fatigue. The initial low intensity stage was eliminated as it was not feasible to collect a large enough volume of air at this intensity during the stage. During a three minute time interval between stages, the bags were analyzed and emptied and the EXPRESS system data were re-entered to start a new test for the next stage. The pneumatic slide valve program was rebooted for the next stage.

Headgear

Headgear was modified as it was front heavy due to the pneumotach and two way Hans Rudolph valves in series being connected to an expiratory hose. Weights equaling 300 g were taped to the right rear of the headgear to offset the weight of the valves and the attached expiratory hose attached on the front left side.

Delay Times

The dead space of the housing and mouth port combined with the pneumotach for the set-up was found in the literature to be 122.9 ml. This was then entered into the EXPRESS system global set-up. The dead space for the manual bag system was not a concern as the stages were three minutes in length and the subject was assumed to have achieved steady state prior to sampling. Therefore, the air remaining in the housing and tubing from the previous stage had been flushed by steady state gases prior to collection of the next stage.

Drierite

The Drierite container was filled with new Drierite, and the calibration gas was then run so that it read the gas composition accurately when fresh. After one minute, the calibration gas (4% CO_2 and 17% O_2) read 3.97% CO_2 and 16.92% O_2. After two minutes, the calibration gas read 4.00% CO_2 and 16.98% O_2 and remained in this range over the next two days. Therefore, to eliminate any potential problems that could arise as a result of the dessicant used with the manual gas analysis becoming moist, Drierite was changed each day of testing and calibration gas was run through the analyzers for two minutes each time the Drierite was changed prior to any sampling.

Resistance of the Set-Up

When things are set-up in series, air resistance may result from the valves and narrow openings and tubing that are connected together. To determine any effects the

resistance of the series had on respiratory variables, differing tubing lengths were used while a runner ran at 2.68 m/s (6.0 mph) steady state. The slide valve was also removed from the set-up. The bags were analyzed and the variables were compared.

Table 5

Resistance Arising from the Series Set-Up Determined by Manual Analysis

	V_E (L/min)	VO_2 (L/min)	VCO_2 (L/min)
1.25 Foot Hose	65.66	2.25	2.07
5 Foot Hose	60.87	2.21	2.10
6 Foot Hose	62.30	2.08	2.06
No Slide Valve	58.17	2.16	1.84

Next, just using the EXPRESS system the resistance and/or effects of the one-way valves and the headgear were assessed. Overall, the amount of resistance resulting from the manual equipment set-up does not seem to affect the respiratory variables being measured.

Table 6

Effects of Valves and Headgear as Determined by the CPX EXPRESS

	V_E (L/min)	VO_2 (L/min)	VCO_2 (L/min)
Pneumotach only	53.63	1.97	1.86
Pneumotach w/ mouthpiece	55.29	1.85	1.72
Mouthpiece w/ headgear & valves	61.9	2.13	2.09
Whole set-up	64.59	2.11	2.06
With valves & w/o headgear	59.82	2.078	1.99

Sources of Error in the Manual System

All of the steps in manual air analysis were analyzed in order to determine the percent error of each step and to minimize any possible error. The largest error can arise from the volume measurement via the Tissot tank. These error percentages were inserted in equations determining $\dot{V}O_2$. The original $\dot{V}O_2$ from a pilot test was 3.85 L/min. Each variable was manipulated within its range of error to determine what effect it would have on final $\dot{V}O_2$. (Table 7 and Appendix D).

Table 7

Range in $\dot{V}O_2$ Error's Manual Measurement Could Cause

Variable Manipulated	Range of Final VO_2 Values (L/min)
Tissot Initial Reading	3.84-3.87
Tissot Final Reading	3.84-3.87
Tissot Volume	3.83-3.90
O_2	3.84-3.87
CO_2	3.85-3.86
Flow Rate	3.85
Gas Collection Time	3.84-3.87
Temperature	3.84-3.87
Barometric Pressure	3.85-3.86

The variance ranged from -0.52% to 1.30% of $\dot{V}O_2$ by manipulating different error sources. These manual bag measurement variables may not affect final $\dot{V}O_2$ value's, such as with the percent error of the flow rate, to affecting the final $\dot{V}O_2$ value by 0.05 L/min when off within the error range of the Tissot at both the initial and final readings.

PROCEDURES

Subjects received written instructions of the testing protocol and were asked to sign an informed consent and fill out a health history questionnaire. The subjects each performed a discontinuous graded exercise test consisting of three minute stages to exhaustion on a Quinton 3040 treadmill. Testing protocol as seen in Table 8 alters % grade for the first three stages and speed thereafter. A Polar heart rate watch was used to monitor heart rates during testing.

Table 8

Treadmill Protocol

Stage	Speed m/sec (mph)	Grade (%)
1	2.68 (6.0)	0
2	2.68 (6.0)	5
3	2.68 (6.0)	10
4	3.13 (7.0)	10
5	3.57 (8.0)	10
6	4.02 (9.0)	10

The manual bag system gas analyzers and EXPRESS gas analyzers were calibrated prior to each test. The subject wore a nose clip to prevent nasal breathing. A Hans Rudolph head support with a rubber mouthpiece connected in series to a pneumotach was then connected to two separate Hans Rudolph one-way breathing valves. The expired side of the valve was connected via tubing to a pneumatic slide valve controlled by a computer. The slide valve was connected by a two way valve attached to

a neoprene latex meteorological bag. The valve opened and closed during the inspiratory phase in order to collect all expired gases during the timed interval using compressed air to open and close the valve. Exact time of the collection period was recorded both by the slide valve computer and the EXPRESS. It was noted that these times differed by 0.20-0.40 s with the EXPRESS reading a slightly longer time interval probably due to a software issue.

Expired gases were collected from the runners for 30 s during the last minute of each stage. The EXPRESS analyzed expired air corresponding with the manual bag collection system. The bag was shaken prior to analysis to evenly mix the contents. During manual analysis, gases were run through a Drierite desiccant before the contents were analyzed with electronic analyzers. Air was sampled from the bag at a rate of approximately 200 ml/min and exact values were recorded to correct for total volumes measured via the Tissot. The subject values are recorded in Appendix E.

STATISTICAL ANALYSIS

The independent variable was the method used to measure oxygen uptake. It consisted of two levels: the manual bag method and the EXPRESS. The dependent variables were the gas exchange variables: $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$.

Simple regressions were first run between data from Trial 1 and Trial 2 to determine that the EXPRESS system is reliable and then run between the manual bag and EXPRESS for Trial 1 and Trial 2 to check reliability between the systems. If the reliability is poor, by definition the system cannot be valid or accurate. A regression was

then run for $\dot{V}O_{2\ max}$ between the two systems and a 95% confidence interval for these data was developed. Repeated ANOVA's were run for each dependent variable on stage 1, 2 and 3. Three separate MANOVA's were used to determine if differences existed at stage 4, 5, or 6 for $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$.

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APPENDICES

APPENDIX A

MANUSCRIPT

MANUSCRIPT

INTRODUCTION

Maximal oxygen uptake ($\dot{V}O_{2\ max}$) is used to predict athletic performance or determine aerobic capacity. In the early 20th century, the measurement of respiratory variables was very time consuming due to the chemical analysis and calculation of the respiratory gases. New systems are being developed that are less bulky, less expensive and produce results on a breath-by-breath basis. Each time such a system comes on the market, it is important that it be tested to make sure that it accurately measures respiratory variables over a wide range of aerobic capacities. Such studies are most commonly done using the manual bag method as the gold standard.

The Medical Graphics CPX EXPRESS has previously been determined to be accurate for $\dot{V}O_2$ ranging from 2.90-4.76 L/min with a maximal system error of 2.2% throughout this range. In order to market such a system to athletic populations, the EXPRESS needed to be tested at higher ventilation's to determine if there are significant differences at $\dot{V}O_2$ values consistently higher than 4.0 L/min. The purpose of this study was to test the accuracy and reliability of the Medical Graphics CPX EXPRESS using the traditional Douglas bag as the gold standard.

METHODS

An Ametek Applied Electrochemistry zirconia based O_2 fuel cell analyzer (S-3A) and infrared sensor CO_2 analyzer (CD-3A) were warmed for 30 minutes to assure stable

operation. They were calibrated prior to each test using both the calibration gas (12% O_2 and 5% CO_2) and reference gas (21% O_2) that were also used by the EXPRESS system. As described in the owner's manual, the EXPRESS system analyzers were warmed up for 30 minutes, the pump was warmed up for 10 minutes and the system was then ready for use.

During pilot testing, a 3.0 L Hans Rudolph calibration syringe was used to calibrate the Tissot bell factor, which was changed to 3.18 L/min to adjust for the 2.09% difference between syringe and Tissot values. The syringe may have been off by up to 1.0%, however, as the syringe was used to calibrate both the manual bag and EXPRESS systems so this was not a concern as both would be off by the same percentage. To check for any drift, the manual analyzers were calibrated initially with reference and calibration gases. After two hours, the O_2 was within 0.04% and the CO_2 within 0.01% of actual concentrations.

The dead space of the housing and mouth port combined with the pneumotach for the set-up was found in the literature to be 122.9 ml. This was entered into the EXPRESS system global set-up. The dead space for the manual system was not a concern as the stages were three minutes in length and the subject was assumed to have achieved steady state prior to sampling. Therefore, the air remaining in the housing and tubing from the previous stage had been flushed by steady state gases prior to collection of gases at the current stage.

The Drierite container was filled with fresh Drierite each test day. Pilot studies found that after changing Drierite, the O_2 and CO_2 concentrations did not stabilize at the

correct reference reading for two minutes. Therefore, calibration gas was run through the manual analyzers for two minutes prior to any sample collections to eliminate potential problems that could arise from a change in O_2 or CO_2 concentrations as a result of the desiccant.

All of the steps in manual air analysis were analyzed in order to determine the percent error of each step and to minimize any possible error. The largest error can arise from the volume measurement via the Tissot tank. These error percentages were inserted in equations determining $\dot{V}O_2$. The original $\dot{V}O_2$ from a pilot test was 3.85 L/min. Each variable was manipulated within its range of error to determine what effect it would have on final $\dot{V}O_2$. (Table 1 and Appendix D).

Table 1

Range in $\dot{V}O_2$ Error's in Manual Measurement Could Cause

Variable Manipulated	Range of Final VO_2 Values (L/min)
Tissot Initial Reading	3.84-3.87
Tissot Final Reading	3.84-3.87
Tissot Volume	3.83-3.90
O_2	3.84-3.87
CO_2	3.85-3.86
Flow Rate	3.85
Gas Collection Time	3.84-3.87
Temperature	3.84-3.87
Barometric Pressure	3.85-3.86

The variance ranged from -0.52% to 1.30% of $\dot{V}O_2$ by manipulating different error sources. These manual bag measurement variables may not affect final $\dot{V}O_2$ value's, such as with the percent error of the flow rate, to affecting the final $\dot{V}O_2$ value by 0.05 L/min when off within the error range of the Tissot at both the initial and final readings.

Following approval by the Institution Review Board, 12 male endurance athletes between the ages of 19 and 37 years (M=24.67±5.25 yr.) reported to the Human Performance Laboratory at St. Cloud State University (SCSU) on two separate testing occasions. They were recruited from SCSU athletic teams and through word of mouth at the SCSU Human Performance Lab. Each subject signed an informed consent form and completed a health history questionnaire.

The test protocol consisted of a discontinuous graded exercise test with three minute stages to exhaustion on a Quinton 3040 treadmill. The testing protocol altered percent grade by 5% for the first three stages (0%, 5%, and 10%) at a constant 2.68 m/s (6.0 mph) speed followed by 0.45 m/s (1.0 mph) increases in speed at a constant 10% grade.

During a three minute time interval between stages, the bags were analyzed and emptied and the EXPRESS system data were re-entered to start a new test for the next stage. A Polar heart rate watch was used to monitor heart rate during testing and blood pressure was taken before and after testing. Subjects wore a nose clip to prevent nasal breathing. A Hans Rudolph head support with a rubber mouthpiece connected in series to the pneumotach was then connected to two separate Hans Rudolph one-way breathing valves. The expired side of the valve was connected via tubing to a pneumatic slide valve controlled by a computer. The slide valve was connected by a two-way valve attached to a neoprene latex 120 L bag. The valve opened and closed during the inspiratory phase in order to collect all expired gases during the timed interval using compressed air to open and close the valve. The EXPRESS recorded exact time of the collection period.

Expired gases were collected from the subjects for 30 seconds during the last minute of each stage while the EXPRESS analyzed expired air that corresponded to the manual bag system. During manual bag analysis, gases were first run through a Drierite desiccant before the contents were analyzed with the electronic analyzers. The bag was shaken prior to manual bag analysis to evenly mix the contents. Air was sampled from the bag and the volumes of gas used in manual analysis were recorded so they could be later added to the volumes measured via the Tissot for an accurate total gas volume measurement.

Statistically, the independent variable was the method used to measure oxygen uptake. It consisted of two levels: the manual bag method and the EXPRESS. The dependent variables were the gas exchange variables: $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$. Simple regressions were first run between data from Trial 1 and Trial 2 to determine that the EXPRESS system is reliable and then run between the manual bag and EXPRESS for Trial 1 and Trial 2 to check reliability between systems. If the reliability is poor, by definition the system cannot be accurate or valid. A regression was then run for $\dot{V}O_{2\ max}$ between the two systems and a 95% confidence interval for these data was developed. Repeated ANOVA's were run for each dependent variable on stages 1, 2 and 3. Three separate MANOVA's were used to determine if differences existed at stage 4, 5, or 6 for $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$.

RESULTS

Table 2 shows results from the manual bag method and EXPRESS systems. The EXPRESS system was as reliable as the manual bag method with data averaged across all stages.

Table 2

Reliability Regression Data within System

		r	r^2	RMS (L/min)	Equation
$\dot{V}_E$	Manual Test 1 vs. 2	0.98	0.96	7.89	y=1.00(x)+1.62
	EXPRESS Test 1 vs. 2	0.97	0.94	8.68	y=0.98(x)+2.19
$\dot{V}O_2$	Manual Test 1 vs. 2	0.98	0.96	0.17	y=1.01(x)-0.07
	EXPRESS Test 1 vs. 2	0.98	0.96	0.16	y=1.00(x)-0.08
$\dot{V}CO_2$	Manual Test 1 vs. 2	0.98	0.97	0.22	y=1.00(x)-0.01
	EXPRESS Test 1 vs. 2	0.98	0.96	0.23	y=0.97(x)+0.05

With reliability for each system established, reliability between systems was tested and was also high from test to test using data averaged across the stages.

Table 3

Reliability Regression Data between System

		r	r^2	RMS (L/min)	Equation
$\dot{V}_E$	Manual vs. EXPRESS Test 1	1.00	1.00	2.26	y=0.99(x)+1.91
	Manual vs. EXPRESS Test 2	1.00	0.99	3.17	y=0.97(x)+2.15
$\dot{V}O_2$	Manual vs. EXPRESS Test 1	0.99	0.99	0.09	y=0.96(x)+0.15
	Manual vs. EXPRESS Test 2	0.98	0.97	0.14	y=0.94(x)+0.16
$\dot{V}CO_2$	Manual vs. EXPRESS Test 1	1.00	0.99	0.10	y=1.00(x)+0.11
	Manual vs. EXPRESS Test 2	0.99	0.99	0.14	y=0.97(x)+0.18

A regression was performed for $\dot{V}O_{2\ max}$ between the two systems yielding a high correlation [r=0.92, r^2=0.85 (y=1.00x-0.11)]. As O_2 consumption was the main concern in this study, a 95% confidence interval was established using $\dot{V}O_{2\ max}$ data from all trials using the following equation:

$$S=(S_D^2+0.25(S_1)^2+0.25(S_2)^2)^{0.5}$$

where S_D was the standard deviation of the difference between the manual bag method and EXPRESS system, S_1 was the standard deviation of the difference between manual bag trials and S_2 was the standard deviation of the difference between EXPRESS trials. This interval, resulted in an acceptable deviation of ±0.15 L/min (1). Of the 23 max trials, 18 fell into this confidence interval for $\dot{V}O_2$ and another four fell within 50 ml--less than a 5% difference. Only one max value did not fall into this acceptable range.

All 12 subjects ran at least four stages. Nine subjects completed five stages and four subjects completed six stages. Table's 4, 5 and 6 show mean $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$ (±SE) respectively for each stage.

Table 4

Mean V_E (±SE) in L/min

Stage (N=12)	Manual Bag Method		EXPRESS	
	Mean (L/min)	SE	Mean (L/min)	SE
1	61.48	1.43	61.73	1.45
2	79.60	2.43	79.44	2.30
3	107.95	3.88	107.78	3.81
4	129.17	4.03	129.55	3.85
5 (n=9)	149.15	3.39	148.01	3.28
6 (n=4)	159.98	3.88	158.02	5.25

Table 5

Mean VO_2 (±SE) in L/min

Stage (N=12)	Manual Bag Method		EXPRESS	
	Mean (L/min)	SE	Mean (L/min)	SE
1	2.55	0.04	2.56	0.04
2	3.14	0.05	3.15	0.05
3	3.87	0.06	3.82	0.07
4	4.34	0.05	4.31	0.05
5 (n=9)	4.61	0.07	4.54	0.07
6 (n=4)	4.83	0.10	4.68	0.13

Table 6

Mean VCO_2 (±SE) in L/min

Stage (N=12)	Manual Bag Method		EXPRESS	
	Mean (L/min)	SE	Mean (L/min)	SE
1	2.25	0.05	2.34	0.05
2	2.94	0.07	3.03	0.07
3	3.97	0.09	4.03	0.09
4	4.63	0.08	4.72	0.08
5 (n=9)	5.20	0.10	5.25	0.09
6 (n=4)	5.50	0.14	5.47	0.17

The first three stages were analyzed using repeated measures ANOVA simply to check for differences apparent at lower intensities with an adjusted p-value of 0.0167 (for three stages). There were no significant differences for $\dot{V}_E$ at any stage. There were no significant differences for $\dot{V}O_2$. There were significant differences for mean $\dot{V}CO_2$ between systems for stages 1 and 2. For stage 1, there was a 3.8% difference and for stage 2 the difference was 3.0%.

A Multivariate Analysis of Variance (MANOVA) was run for stages 4, 5 and 6 as this study was primarily concerned with higher volumes and $\dot{V}O_2$ values. There was no

interaction between the two test times or the two different systems for $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$. There were also no significant differences for main effects of system or test time. Table 7 shows the results of the MANOVA for stages 4, 5 and 6.

Table 7

MANOVA's 4, 5 and 6

Stage		Wilks' Lambda	F-Value	P-Value
Stage 4	System	0.92	1.19	0.32
	Time	0.96	0.52	0.70
	System* Time	1.00	0.05	0.99
Stage 5	System	0.88	1.35	0.28
	Time	0.98	.019	0.90
	System* Time	1.00	0.01	1.00
Stage 6	System	0.89	0.42	0.74
	Time	0.85	0.60	0.63
	System* Time	0.98	0.08	0.97

DISCUSSION

Overall, results of the Medical Graphics EXPRESS suggest that the system could be used for the measurement of respiratory gas exchange variables throughout a range of intensities from 1.0-5.18 L/min with little difference in results from a manual bag method. This study followed similar methods to that done by Walshlager et al.; however, the statistical analyses used in this study reviewed each stage individually for differences between systems as well as establishing a 95% confidence interval for $\dot{V}O_{2\ max}$ values.

The reliability information gathered from regression analyses suggest that the EXPRESS is as reliable as the manual bag method for within system tests (r=0.97-0.98) and also that the reliability is high between systems (r=0.97-1.00). Other studies

analyzing test-retest reliability within a system have reported correlation's of r=0.78 for $\dot{V}_E$ (10) and r=0.95-1.00 for $\dot{V}O_2$ (4, 6, 10). Studies looking at correlation's between systems have found r=0.86-1.00 for $\dot{V}_E$ (4, 5, 9), r=1.00 for $\dot{V}CO_2$ (5, 9) and r=0.90-0.98 for $\dot{V}O_2$ (4, 9).

In clinical measurement, comparison of a new measurement technique with an established one is often needed to see whether they agree sufficiently for the new to replace the old. Calculating the bias, estimated by the mean difference and the standard deviation of the differences can summarize the lack of agreement. Any differences within two standard deviations are not usually clinically important so the manual bag and EXPRESS are interchangeable if the data fall within these limits. However, a new sample population may produce different limits. If repeated measurements are done on each subject using both methods, the mean of each method on each subject is calculated and these pairs of means are used to compare the two methods (1). The fact that 18 of 23 $\dot{V}O_{2\ max}$ trials fell within the established 95% confidence interval lends support to the accuracy of the EXPRESS. Katch et al. found a variance of ±11.2% at two standard deviations when doing 8-20 repeat $\dot{V}O_{2\ max}$ tests. Ninety percent was due to biological variation and less than 10% due to technological error (2). EXPRESS data had a maximal variance of 11.7% at two standard deviations.

Accuracy data obtained from the ANOVA's suggest that the EXPRESS is as accurate as a manual bag method when measuring $\dot{V}_E$ and $\dot{V}O_2$. The $\dot{V}CO_2$ was significantly different for stages 1, 2 and 4. This may have been due to the sensitivity of the equipment. Values for $\dot{V}CO_2$ are known to change from the beginning to the end of

exhalation, so $\dot{V}CO_2$ values may be affected more so than $\dot{V}O_2$. Other studies looking at differences between a breath-by-breath system and the manual bag found no significant difference for $\dot{V}_E$, (4, 5, 8) $\dot{V}O_2$ (4, 5, 7, 8) or $\dot{V}CO_2$ between values (8). One study found values for $\dot{V}CO_2$ were significantly higher with the differences increasing as the test progressed (5). In most studies however, percent differences between systems were often less than 4.5-6.0% for $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$ (4, 7, 11).

The EXPRESS system did present some unique challenges during operation. The model used in this study allowed only one test to be stored at any one time. Once a new test was initiated, data from the previous test was automatically erased. This was problematic in this study since six separate stages for each subject had to be entered each as a new test. When data from the old test were erased, data could no longer be changed if subject information was entered incorrectly. There was no hard copy record of these data either in case something were to happen to the paper copy.

Occasional systematic errors in the EXPRESS system were also encountered. The system would unpredictably display various error messages, interrupting the test. Whenever this happened, data were lost and the system needed to be re-booted. A standard 10 minute warm-up was then required before testing could be resumed. In the average test situation this could be problematic because the individual may have completed several stages of a fitness test before resuming testing. Thus, the individual may be slightly fatigued and unable to perform optimally. An additional dilemma might be encountered when tests are scheduled at a clinic or physician's office. Time

scheduling is precise and any disruption in the day would make it difficult to resume a test that was prematurely aborted.

Overall, the EXPRESS system is not different from the manual bag method when measuring $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$ except at low levels ($\dot{V}CO_2 \leq 2.94$ L/min). The EXPRESS system appears to be reliable and accurate at intensities up to 5.18 L/min for male endurance athletes. It would therefore be acceptable to use the EXPRESS under conditions similar to those tested in this study, especially in a similar range of intensities. Additional testing of the EXPRESS is recommended as system failures occurred throughout testing while using two different EXPRESS systems. Random testing off the assembly line would help to show whether the EXPRESS can perform without system failures when doing repeat $\dot{V}O_{2\ max}$ tests.

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APPENDIX B

INFORMED CONSENT AND PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

INFORMED CONSENT FOR MAXIMAL TREADMILL EXERCISE TESTING

You are invited to participate in a study of the assessment of the CPX EXPRESS respiratory gas exchange system. This study has been designed as a thesis project for Amy Keranen's Masters degree in Exercise Physiology to learn if the EXPRESS system is accurate at high volumes of expired air. You were selected as a possible participant in this study because you are a well conditioned male athlete.

If you decide to participate, Amy will monitor your heart rate at each stage of a maximal treadmill graded exercise test and your blood pressure before and after each test. Each stage will last three minutes with gases being collected during the last portion of each stage. The test will be discontinuous, thus, there will be a short rest period between each stage while the researcher analyzes the gases in the bags. The speed and grade of the treadmill will increase at each stage until fatigue sets in or you wish to discontinue the test for any other reason. The test duration will be approximately 30 minutes in length. Each subject will receive a printout containing their $\dot{V}O_2$ max indicating cardiovascular endurance. Potential physical risk associated with the testing includes acute fatigue which is minimal as you are highly trained athletes and this is something you have encountered numerous times. All testing procedures will be those practiced at the St. Cloud State Human Performance Laboratory designed to minimize risks.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and be disclosed only with your permission. The results in the form of coded numbers will be forwarded to the Medical Graphics Corporation in St. Paul, Minnesota as this thesis project has been done using their equipment with the knowledge that the results may be used in their marketing department.

Your decision whether or not to participate will not prejudice your future relations with the St. Cloud State Human Performance Laboratory. If you decide to participate, you are free to discontinue participation at any time without prejudice. If you have any questions, please ask either before beginning or at any point during the testing session. If you have any additional questions later, Amy Keranen (255-2373) will be happy to answer them as will Dr. Dave Bacharach (255-3105).

Your signature indicates that you have read the information provided above and have decided to participate. You may withdraw at any time without prejudice after signing this form should you chose to discontinue participation in this study.

_____ _____

Signature Date

PAR-Q

(A Questionnaire for People Aged 15 to 69)

YES	NO	
___	___	1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
___	___	2. Do you feel pain in your chest when you do physical activity?
___	___	3. In the past month, have you had chest pain when you were not doing physical activity?
___	___	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
___	___	5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?
___	___	6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
___	___	7. Do you know of any other reason why you should not do physical activity?

If you answered:

YES to one or more questions:

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal.

- You may be able to do any activity you want--as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions:

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active--begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal--this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever--wait until you feel better; or
- if you are or may be pregnant--talk to your doctor before you start becoming active.

I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction.

SIGNATURE_____ DATE_____

Referenced from ACSM's Guideline for Exercise Testing and Presciption, 5th edition.

APPENDIX C

TISSOT BELL FACTOR DATA

10/22/97	Day 1			
Syringe Vol. (L)	Tissot (cm)	Tissot Vol. (L)	Total Tissot Vol. (L)	% Difference
0	24.00			
3	25.00	3.24	3.24	7.52
6	25.90	2.92	6.16	2.65
9	26.90	3.24	9.41	4.33
12	27.85	3.08	12.49	3.92
15	28.80	3.08	15.57	3.67
18	29.70	2.92	18.49	2.65
21	30.70	3.24	21.73	3.38
24	31.60	2.92	24.65	2.65
27	32.60	3.24	27.90	3.22
30	33.55	3.08	30.98	3.16
33	34.50	3.08	34.06	3.12
36	35.40	2.92	36.98	2.65
39	36.40	3.24	40.23	3.05
42	37.30	2.92	43.15	2.65
45	38.25	3.08	46.23	2.65
48	39.20	3.08	49.31	2.65
51	40.10	2.92	52.23	2.35
54	41.10	3.24	55.47	2.65
57	42.05	3.08	58.55	2.65
60	43.00	3.08	61.64	2.65
63	43.90	2.92	64.56	2.41
66	44.90	3.24	67.80	2.65
69	45.80	2.92	70.72	2.43
72	46.80	3.24	73.96	2.65
75	47.65	2.76	76.72	2.24
78	48.60	3.08	79.80	2.26
81	49.50	2.92	82.72	2.08
84	50.50	3.24	85.97	2.29
87	51.40	2.92	88.89	2.12
90	52.35	3.08	91.97	2.14
93	53.30	3.08	95.05	2.16
96	54.20	2.92	97.97	2.01
99	55.10	2.92	100.89	1.87
102	56.10	3.24	104.13	2.05
105	57.05	3.08	107.21	2.07
108	58.00	3.08	110.30	2.08
111	59.00	3.24	113.54	2.24
114	59.50	1.62	115.16	1.01
Average % Difference From 70-100 Liters				
		2.17		
Temp (F)	69.00			
Pressure (mmHg)	737.00			
Humidity (%)	31.00			
Time-pm	0.13			

10/23/97	Day 2			
Syringe Vol. (L)	Tissot (cm)	Tissot Vol. (L)	Total Tissot Vol. (L)	% Difference
0	24.50			
3	25.45	3.08	3.08	2.65
6	26.45	3.24	6.33	5.15
9	27.40	3.08	9.41	4.33
12	28.30	2.92	12.33	2.65
15	29.25	3.08	15.41	2.65
18	30.20	3.08	18.49	2.65
21	31.10	2.92	21.41	1.92
24	32.05	3.08	24.49	2.01
27	33.00	3.08	27.57	2.08
30	33.95	3.08	30.66	2.14
33	34.90	3.08	33.74	2.19
36	35.85	3.08	36.82	2.23
39	36.80	3.08	39.90	2.26
42	37.75	3.08	42.98	2.29
45	38.70	3.08	46.06	2.31
48	39.65	3.08	49.15	2.33
51	40.60	3.08	52.23	2.35
54	41.50	2.92	55.15	2.08
57	42.45	3.08	58.23	2.11
60	43.40	3.08	61.31	2.14
63	44.35	3.08	64.39	2.16
66	45.30	3.08	67.48	2.19
69	46.25	3.08	70.56	2.21
72	47.15	2.92	73.48	2.01
75	48.10	3.08	76.56	2.04
78	49.05	3.08	79.64	2.06
81	50.00	3.08	82.72	2.08
84	50.90	2.92	85.64	1.92
87	51.90	3.24	88.89	2.12
90	52.85	3.08	91.97	2.14
93	53.80	3.08	95.05	2.16
96	54.70	2.92	97.97	2.01
99	55.60	2.92	100.89	1.87
102	56.60	3.24	104.13	2.05
105	57.55	3.08	107.21	2.07
108	58.50	3.08	110.30	2.08
111	59.45	3.08	113.38	2.10
114	60.40	3.08	116.46	2.11
Average % Difference From 70-100 Liters				
		2.04		
Temp (F)	69.00			
Pressure (mmHg)	733.00			
Humidity (%)	32.00			
Time-am	0.06			

10/24/97	Day 3			
Syringe Vol. (L)	Tissot (cm)	Tissot Vol. (L)	Total Tissot Vol. (L)	% Difference
0	30.95			
3	31.90	3.08	3.08	2.65
6	32.90	3.24	6.33	5.15
9	33.85	3.08	9.41	4.33
12	34.80	3.08	12.49	3.92
15	35.80	3.24	15.73	4.66
18	36.70	2.92	18.65	3.50
21	37.65	3.08	21.73	3.38
24	38.60	3.08	24.82	3.29
27	39.55	3.08	27.90	3.22
30	40.50	3.08	30.98	3.16
33	41.40	2.92	33.90	2.65
36	42.40	3.24	37.14	3.08
39	43.30	2.92	40.06	2.65
42	44.30	3.24	43.31	3.02
45	45.25	3.08	46.39	2.99
48	46.20	3.08	49.47	2.97
51	47.10	2.92	52.39	2.65
54	48.10	3.24	55.63	2.94
57	49.00	2.92	58.55	2.65
60	49.90	2.92	61.47	2.40
63	50.85	3.08	64.56	2.41
66	51.80	3.08	67.64	2.42
69	52.75	3.08	70.72	2.43
72	53.70	3.08	73.80	2.44
75	54.60	2.92	76.72	2.24
78	55.60	3.24	79.96	2.46
81	56.50	2.92	82.88	2.27
84	57.50	3.24	86.13	2.47
87	58.40	2.92	89.05	2.30
90	59.30	2.92	91.97	2.14
93	60.25	3.08	95.05	2.16
96	61.20	3.08	98.13	2.17
99	62.15	3.08	101.21	2.19
102	63.10	3.08	104.29	2.20
105	64.05	3.08	107.38	2.21
108	65.00	3.08	110.46	2.23
111	65.90	2.92	113.38	2.10
Average % Difference From 70-100 Liters				
		2.28		
Pressure (mmHg)	743.00			
Humidity (%)	31.00			
Time-am	0.30			

10/25/97	Day 4			
Syringe Vol. (L)	Tissot (cm)	Tissot Vol. (L)	Total Tissot Vol. (L)	% Difference
0	12.70			
3	13.70	3.24	3.24	7.52
6	14.65	3.08	6.33	5.15
9	15.65	3.24	9.57	5.95
12	16.60	3.08	12.65	5.15
15	17.55	3.08	15.73	4.66
18	18.50	3.08	18.82	4.33
21	19.40	2.92	21.73	3.38
24	20.35	3.08	24.82	3.29
27	21.30	3.08	27.90	3.22
30	22.25	3.08	30.98	3.16
33	23.20	3.08	34.06	3.12
36	24.15	3.08	37.14	3.08
39	25.10	3.08	40.23	3.05
42	26.00	2.92	43.15	2.65
45	26.95	3.08	46.23	2.65
48	27.95	3.24	49.47	2.97
51	28.90	3.08	52.55	2.95
54	29.80	2.92	55.47	2.65
57	30.75	3.08	58.55	2.65
60	31.70	3.08	61.64	2.65
63	32.60	2.92	64.56	2.41
66	33.55	3.08	67.64	2.42
69	34.50	3.08	70.72	2.43
72	35.40	2.92	73.64	2.23
75	36.35	3.08	76.72	2.24
78	37.30	3.08	79.80	2.26
81	38.20	2.92	82.72	2.08
84	39.15	3.08	85.80	2.10
87	40.10	3.08	88.89	2.12
90	41.00	2.92	91.81	1.97
93	41.90	2.92	94.72	1.82
96	42.85	3.08	97.81	1.85
99	43.80	3.08	100.89	1.87
102	44.75	3.08	103.97	1.89
105	45.70	3.08	107.05	1.92
108	46.60	2.92	109.97	1.79
111	47.55	3.08	113.05	1.82
114	48.50	3.08	116.14	1.84
Average % Difference From 70-100 Liters				
		2.04		

10/28/97	Day 5			
Syringe Vol. (L)	Tissot (cm)	Tissot Vol. (L)	Total Tissot Vol. (L)	% Difference
0	13.90		0.00	
3	14.85	3.08	3.08	2.65
6	15.80	3.08	6.16	2.65
9	16.75	3.08	9.25	2.65
12	17.70	3.08	12.33	2.65
15	18.65	3.08	15.41	2.65
18	19.60	3.08	18.49	2.65
21	20.50	2.92	21.41	1.92
24	21.50	3.24	24.65	2.65
27	22.45	3.08	27.74	2.65
30	23.35	2.92	30.66	2.14
33	24.45	3.57	34.22	3.58
36	25.30	2.76	36.98	2.65
39	26.30	3.24	40.23	3.05
42	27.25	3.08	43.31	3.02
45	28.20	3.08	46.39	2.99
48	29.15	3.08	49.47	2.97
51	30.05	2.92	52.39	2.65
54	31.00	3.08	55.47	2.65
57	31.90	2.92	58.39	2.38
60	32.85	3.08	61.47	2.40
63	33.80	3.08	64.56	2.41
66	34.70	2.92	67.48	2.19
69	35.60	2.92	70.39	1.98
72	36.55	3.08	73.48	2.01
75	37.45	2.92	76.40	1.83
78	38.40	3.08	79.48	1.86
81	39.35	3.08	82.56	1.89
84	40.30	3.08	85.64	1.92
87	41.25	3.08	88.72	1.94
90	42.15	2.92	91.64	1.79
93	43.10	3.08	94.72	1.82
96	44.05	3.08	97.81	1.85
99	45.00	3.08	100.89	1.87
102	45.95	3.08	103.97	1.89
105	46.85	2.92	106.89	1.77
108	47.80	3.08	109.97	1.79
111	48.75	3.08	113.05	1.82
114	49.65	2.92	115.97	1.70
Average % Difference From 70-100 Liters				
		1.88		

10/29/97	Day 6			
Syringe Vol.(L)	Tissot (cm)	Tissot Vol. (L)	Total Tissot Vol.(L)	% Difference
0	30.00			
3	31.05	3.41	3.41	11.93
6	32.00	3.08	6.49	7.52
9	32.95	3.08	9.57	5.95
12	33.90	3.08	12.65	5.15
15	34.85	3.08	15.73	4.66
18	35.80	3.08	18.82	4.33
21	36.75	3.08	21.90	4.10
24	37.65	2.92	24.82	3.29
27	38.60	3.08	27.90	3.22
30	39.55	3.08	30.98	3.16
33	40.50	3.08	34.06	3.12
36	41.45	3.08	37.14	3.08
39	42.40	3.08	40.23	3.05
42	43.30	2.92	43.15	2.65
45	44.30	3.24	46.39	2.99
48	45.20	2.92	49.31	2.65
51	46.15	3.08	52.39	2.65
54	47.05	2.92	55.31	2.37
57	48.00	3.08	58.39	2.38
60	48.90	2.92	61.31	2.14
63	49.85	3.08	64.39	2.16
66	50.80	3.08	67.48	2.19
69	51.75	3.08	70.56	2.21
72	52.70	3.08	73.64	2.23
75	53.65	3.08	76.72	2.24
78	54.55	2.92	79.64	2.06
81	55.50	3.08	82.72	2.08
84	56.45	3.08	85.80	2.10
87	57.40	3.08	88.89	2.12
90	58.35	3.08	91.97	2.14
93	59.30	3.08	95.05	2.16
96	60.20	2.92	97.97	2.01
99	61.15	3.08	101.05	2.03
102	62.10	3.08	104.13	2.05
105	63.00	2.92	107.05	1.92
108	63.95	3.08	110.13	1.94
111	64.90	3.08	113.22	1.96
114	65.80	2.92	116.14	1.84
Average % Difference From 70-100 Liters				
		2.11		

APPENDIX D

MANUAL BAG SOURCES OF ERROR

Manual Bag Sources of Error				
Tissot Errors			**O_2 Analyzer Error**	
L (in the bags)	Error (L)		Analyzer Error	0.01%
70	0.91		Drierite Error	0.00%
80	0.79			
90	0.71			
100	0.64		**CO_2 Analyzer Error**	
Tissot Factor (ml/mm)	317.60		Analyzer Error	0.01%
Error Possible (mm)	2.00		Drierite Error	0.02%
Error Liters (being 2 mm off)	0.64			
Flow Rate % Error			**Rxn. Time Error (s)**	0.15
Off mm on ruler	1.00			
Spirometer Factor (ml/mm)	20.73			
Error Liters	0.02073			
	mm	Liters	% Error (L)	
mm moved by spirometer (per min.)	9.00	0.19	11.11	
	10.00	0.21	10.00	
	11.00	0.23	9.09	
Sample VO_2 Calculation % Error				
		Error Possible		
mm pen moves in Flow Rate	10.00	1 mm		
Flow Time (s)	60.00	0.15 s		
Flow Rate (L/min)	0.21			
O_2	0.1692	0.01%		
CO_2	0.0453	0.02%		
Tissot Initial (cm)	29.70	1 mm		
Tissot Final (cm)	56.20	1 mm		
Tissot Difference (mm)	265.00			
Tissot Volume (L)	84.16	0.75 L		
Gas Analysis Time (s)	45.00	0.15 s		
Flow Volume (L)	0.21			
Total Volume (L)	84.37	83.60		
Volume (L) (STPD)	74.47			
Volume (L) (STPD) per Minute	99.30			
VO_2 (L/min)	3.85			
Room Temperature (C)	20.00	1 deg. C		
Barometric Pressure (mmHg)	738.00	1 mmHg		

APPENDIX E

SUBJECT RAW DATA FROM MANUAL BAG AND CPX EXPRESS SYSTEMS

STAGE 1 DATA							
				Test #1			
Subject	**Max HR**	**V_E (L/min BTPS)**		**VO_2 (L/min)**		**VCO_2 (L/min)**	
		Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	197	67.16	67.60	2.470	2.521	2.326	2.427
2	196	73.89	72.08	2.925	2.878	2.732	2.765
3	197	60.47	60.05	2.600	2.598	2.357	2.375
4		61.40	68.34	2.363	2.632	2.247	2.577
5	195	58.50	58.03	2.654	2.609	2.230	2.256
6	202	52.30	51.27	2.646	2.576	2.208	2.218
7	175	56.52	57.47	2.578	2.680	2.189	2.286
8	187	59.36	59.06	2.556	2.540	2.175	2.205
9	192	62.66	64.16	2.690	2.789	2.212	2.330
10	189	63.24	62.66	2.714	2.687	2.319	2.369
11	200	64.09	64.57	2.567	2.472	2.303	2.306
12	201	55.76	57.61	2.307	2.397	1.987	2.136
				Test #2			
		V_E (L/min BTPS)		**VO_2 (L/min)**		**VCO_2 (L/min)**	
		Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	194	67.45	63.79	2.537	2.398	2.264	2.254
2	196	73.09	73.35	2.810	2.881	2.752	2.826
3	195	62.31	60.75	2.703	2.643	2.527	2.516
4	187	75.07	77.71	2.692	2.788	2.693	2.890
5	191	64.29	62.53	2.609	2.505	2.340	2.305
6	200	51.88	51.81	2.460	2.469	2.183	2.241
7	176	58.23	58.54	2.541	2.630	2.313	2.389
8	187	67.12	67.11	2.440	2.500	2.137	2.276
9	184	61.77	62.33	2.607	2.615	1.877	2.234
10	188	53.78	54.11	2.344	2.365	2.043	2.124
11	188	58.09	58.26	2.317	2.310	1.940	2.042
12	196	47.08	48.20	2.010	2.046	1.694	1.752

STAGE 2 DATA						
			Test #1			
Subject	**V_E (L/min BTPS)**		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	89.49	90.88	3.145	3.131	3.085	3.175
2	96.25	99.52	3.534	3.554	3.535	3.686
3	68.87	71.92	3.095	3.218	2.943	3.094
4	86.20	85.96	3.283	3.275	3.154	3.236
5	75.82	75.49	3.290	3.246	2.927	2.992
6	64.08	65.38	3.142	3.096	2.864	2.919
7	78.96	80.57	3.318	3.408	3.191	3.327
8	76.23	76.55	3.089	3.047	2.745	2.733
9	79.01	82.83	3.272	3.488	2.939	3.200
10	65.92	65.66	2.959	2.913	2.628	2.609
11	75.05	76.90	2.960	2.912	2.642	2.765
12	66.62	70.18	2.685	2.803	2.364	2.677
			Test #2			
	V_E (L/min BTPS)		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	85.75	81.41	3.122	2.926	2.975	2.902
2	100.88	99.20	3.667	3.589	3.790	3.757
3	76.73	76.52	3.354	3.221	3.253	3.160
4	91.42	92.58	3.378	3.418	3.286	3.461
5	80.49	79.02	3.221	3.104	3.070	3.020
6	58.99	61.83	2.855	2.955	2.600	2.733
7	82.02	83.97	3.239	3.356	3.232	3.373
8	84.76	86.25	3.045	3.011	2.807	2.860
9	98.76	99.36	3.457	3.488	3.159	3.277
10	65.50	66.55	2.887	2.910	2.587	2.721
11	73.26	73.59	2.852	2.859	2.464	2.601
12	62.43	64.53	2.541	2.597	2.291	2.404

STAGE 3 DATA						
			Test #1			
Subject	**V_E (L/min BTPS)**		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	120.71	120.65	3.762	3.694	3.954	4.006
2	143.04	143.11	4.290	4.181	4.829	4.900
3	92.41	93.33	3.950	3.957	4.045	4.061
4	115.35	113.78	4.049	4.005	4.120	4.210
5	102.01	100.99	4.008	3.890	4.103	4.106
6	81.36	82.75	3.895	3.819	3.649	3.688
7	114.63	113.15	4.133	4.142	4.449	4.505
8	123.55	124.83	4.040	3.926	4.017	4.012
9	114.64	116.27	4.123	4.275	4.228	4.492
10	94.58	94.94	3.745	3.769	3.679	3.736
11	94.57	96.48	3.319	3.266	3.435	3.530
12	92.60	96.56	3.431	3.521	3.330	3.731
			Test #2			
	V_E (L/min BTPS)		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	118.55	105.42	3.835	3.234	3.970	3.513
2	138.03	136.62	4.282	4.145	4.813	4.781
3	94.29	94.74	3.879	3.872	4.081	4.066
4	118.36	117.61	4.103	4.053	4.236	4.339
5	106.34	104.41	3.946	3.759	4.064	3.986
6	75.68	77.63	3.583	3.616	3.377	3.468
7	122.07	123.42	4.004	4.095	4.460	4.600
8	122.19	125.31	3.901	4.009	3.940	4.156
9	140.35	140.88	4.266	4.211	4.410	4.486
10	86.49	86.03	3.670	3.624	3.498	3.656
11	92.23	92.08	3.323	3.261	3.241	3.282
12	86.85	85.80	3.344	3.309	3.249	3.323

STAGE 4 DATA						
			Test #1			
Subject	**V_E (L/min BTPS)**		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	146.05	146.23	4.123	4.022	4.658	4.721
2	149.65	150.35	4.481	4.375	4.848	4.956
3	119.01	122.50	4.329	4.437	4.763	4.891
4	128.92	131.57	4.348	4.465	4.738	5.001
5	133.89	135.51	4.416	4.402	4.855	5.039
6	93.63	96.73	4.291	4.297	4.207	4.296
7	143.61	139.73	4.611	4.547	5.240	5.270
8	148.70	150.03	4.522	4.587	4.763	4.909
9	140.14	142.01	4.633	4.745	5.002	5.302
10	107.04	106.04	4.337	4.245	4.403	4.356
11	121.82	123.65	4.059	3.968	4.221	4.305
12	109.71	112.86	3.859	3.895	4.093	4.309
			Test #2			
	V_E (L/min BTPS)		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	140.27	138.43	4.182	3.968	4.483	4.441
2	153.46	151.15	4.539	4.474	4.789	4.894
3	126.70	126.03	4.540	4.442	5.005	4.920
4	134.90	135.15	4.513	4.453	4.979	5.048
5	139.56	132.74	4.587	4.214	5.201	4.941
6	90.21	92.18	4.059	4.103	3.997	4.099
7	138.01	138.19	4.394	4.483	5.021	5.136
8	147.05	152.10	4.520	4.530	4.729	4.884
9	160.44	157.38	4.769	4.489	4.836	4.888
10	101.91	102.96	4.077	4.105	4.170	4.312
11	122.64	121.64	4.127	4.048	4.203	4.388
12	102.80	104.06	3.749	3.790	3.895	3.999

STAGE 5 DATA						
			Test #1			
Subject	**V_E (L/min BTPS)**		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	152.35	154.76	4.144	4.125	4.657	4.763
2						
3	142.77	144.31	4.682	4.719	5.361	5.425
4	142.75	139.57	4.856	4.785	3.000	5.589
5	156.42	155.33	4.628	4.511	5.387	5.527
6	120.02		4.653		5.019	
7	158.04	148.96	4.993	4.760	5.348	5.249
8	172.38	171.73	4.842	4.867	5.399	5.501
9						
10	134.19	132.63	4.845	4.765	5.456	5.426
11	135.61	138.66	4.342	4.272	4.645	4.901
12	134.72	136.99	4.256	4.249	5.005	5.176
			Test #2			
	V_E (L/min BTPS)		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1	157.09	153.78	4.315	4.180	4.301	4.390
2						
3	150.49	149.82	4.925	4.728	5.752	5.555
4	139.05	139.39	4.807	4.811	5.556	5.692
5	165.08	158.97	4.765	4.394	5.606	5.455
6	120.55	123.12	4.575	4.632	4.966	5.134
7	170.22	168.70	4.712	4.714	5.691	5.701
8	171.41	173.76	4.850	4.899	5.335	5.459
9						
10	130.61	132.32	4.547	4.561	5.138	5.348
11	142.26	136.13	4.411	4.195	4.684	4.572
12	129.32	128.44	4.097	4.125	4.643	4.742

STAGE 6 DATA						
			Test #1			
Subject	**V_E (L/min BTPS)**		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1						
2						
3	156.09	155.61	4.840	4.803	4.953	4.960
4						
5						
6	152.21	152.76	5.069	4.861	5.671	5.671
7						
8						
9						
10	178.80	180.51	5.177	5.148	6.243	6.355
11	163.29	166.31	4.534	4.413	4.849	5.154
12	163.89	166.89	4.427	4.303	5.239	5.393
			Test #2			
	V_E (L/min BTPS)		**VO_2 (L/min)**		**VCO_2 (L/min)**	
	Manual	EXPRESS	Manual	EXPRESS	Manual	EXPRESS
1						
2						
3	162.24	162.38	5.067	4.967	5.498	5.490
4						
5						
6	142.08	128.24	4.702	4.180	5.479	5.002
7						
8						
9						
10	156.66	155.94	4.898	4.833	5.716	5.817
11						
12	167.86	161.86	4.470	4.314	5.162	5.101