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Pediatric clinical exercise testing system project

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by

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Pediatric Clinical Exercise Testing System

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Abstract

Commercially made exercise testing equipments are designed for testing adults with greater exercise capacity and relatively large minute ventilation compared to pediatric population. As the size of breaths becomes smaller and irregular, as in small children with pulmonary diseases, measurement delay errors may introduce errors to the final results in the exercise testing system. For this reason, a custom made Exercise System was built at the Exercise Laboratory Department at the Hospital for Sick Children. It incorporates a special algorithm that corrects measurement delay errors caused by small breaths. The algorithm calculates the lag time of the expired breath to reach the sampling port and re-aligns the gas concentration reading in time with the corresponding real-time recording of the breath. The Exercise System is currently used for clinical and research purposes. The system shows satisfactory results for adult testing; however, the system requires validation of increase in accuracy of results for testing in pediatrics, especially for ill patients with very small tidal volumes. The main objective of this study is to demonstrate that incorporating the lag time in the algorithm to process and calculate the oxygen (O_2) consumption improves the accuracy of the results in small children exercise testing. In addition, investigate the theory and operation of the Exercise System and document the system designs and testing results for publishing purposes.

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List of Abbreviations

ATPS =Ambient Temperature and Pressure, Saturated.

BTPS=Body Temperature, ambient Pressure, Saturated with water vapor

STPD=Standard Temperature (0 ˚C) and pressure (760 mmHg), Dry

$\dot{V}e$ =Pulmonary expired volume (L/min) (presented in BTPS)

$\dot{V}i$ =Pulmonary inspired volume (L/min) (presented in ATPS)

FiN_2 =Pulmonary fractional inspired concentration of nitrogen

FeN_2=Pulmonary fractional mixed expired concentration of nitrogen

FiO_2= O_2 fraction of the inspired air

$FiCO_2$= CO_2 fraction of the inspired air

FeO_2 =mixed expired oxygen concentration

$FeCO_2$ =mixed expired carbon dioxide concentration

FetCO_2=End-tidal CO_2 concentration

PaCO_2=partial pressure of CO_2 in arterial blood (mmHg)

P_ACO_2=partial pressure of CO_2 in alveolar (mmHg)

PcCO_2=partial pressure of CO_2 in capillary blood (mmHg)

$\dot{V}O_2$ =Volume rate of O_2 production (L/min) (presented in STPD)

$\dot{V}CO_2$ =Volume rate of CO_2 production (L/min) (presented in STPD)

$\dot{V}O_{2\,max}$ =Maximal Oxygen Uptake is measured rigorously in a test that shows a stable oxygen uptake in the face of increasing power.

R =Respiratory exchange ratio

Chapter 1

1.1 Exercise Testing and Clinical Management

Placing the human body under load can bring out abnormalities that are not apparent at rest (Godfrey, S. 1974). These can be factors involved in oxygen uptake/carbon dioxide elimination, cardiovascular system function, and the ability of the exercising muscle to utilize oxygen and nutrients in order to produce energy. Modern exercise testing is capable of isolating one factor from another, thereby pin pointing the pathology.

Many techniques used in clinical assessment become more valuable when repeated on several occasions in any one patient to follow up of the history of a condition or the effect of therapy. This is particularly true for exercise testing, in which a change in overall performance or in the performance of a single mechanism carries greater weight than an absolute value at a single point in time.

With regard to pediatric lung diseases, regular exercise is part of rehabilitation programs pre and post lung transplantation. Repeated testing will provide objective evidence of improvement and identify the mechanisms that underlie any change. It also provides a valuable tool for the physician to use in motivating the patient to continue the activity and in changing the activity to keep it at an optimal level. The results obtained from an exercise test may help in a number of other clinical situations as well, such as respiratory diseases progression.

1.2 Introduction

Ventilation, pulmonary gas transfer, cardiac output, and peripheral blood flow all increase in response to the metabolic demands of working muscles. In disease, structural changes may interfere with these adaptations, causing reduced exercise tolerance, but various mechanisms help to compensate, tending to maintain oxygen supply and carbon

dioxide excretion. Often patient's symptoms are related more to the compensatory mechanisms than to the initial abnormality. In modern exercise testing, the relationship between external work performed and consumption of O_2 and production of CO_2 is measured. The amount of oxygen utilized by the exercising muscle is defined as the oxygen consumption or uptake ($\dot{V}O_2$) expressed in liters per minutes. The amount of carbon dioxide produced by the exercise muscle is defined as the carbon dioxide production ($\dot{V}CO_2$) expressed in liters per minutes. Basically, $\dot{V}O_2$ is the difference between the volume of O_2 inspired per minute and the volume of O_2 expired per minute. $\dot{V}O_2 = (\dot{V}i * FiO_2) - (\dot{V}e * FeO_2)$. Same for $\dot{V}CO_2$, $\dot{V}CO_2 = (\dot{V}e * FeCO_2) - (\dot{V}i * FiCO_2)$. The O_2 fraction of the inspired air FiO_2 =0.2093 and the CO_2 fraction of the inspired air $FiCO_2$ =0.0003 which is usually considered negligible. Of the remaining variables, inspired ventilation ($\dot{V}i$), mixed expired oxygen concentration (FeO_2), and mixed expired carbon dioxide concentration ($FeCO_2$) will be measured experimentally. Expired ventilation ($\dot{V}e$) can be calculated by using the nitrogen balance technique, where nitrogen is treated as an inert gas and the amount of nitrogen entering the body is equated with that leaving.

The exercise system is based on a progressive increment test where the work load is increased by a fixed increment at the end of each minute. In reporting clinical tests, the $\dot{V}O_2$ and $\dot{V}CO_2$ progressively increase over the course of the minute. The value of $\dot{V}O_2$ and $\dot{V}CO_2$ for that work load increment is $\dot{V}O_2$ and $\dot{V}CO_2$ of the last 10 -15 seconds of the minutes.

The fundamentals of the Exercise System are to be able to accurately measure oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) during a known rate of work in a pediatric population. The calculation of the two parameters depends on the measurement techniques of the inspired ventilation, and the mixed expired gas CO_2 and O_2 concentrations.

1.3 End-Tidal CO_2 and Mixed Expired CO_2

At the end of inspiration, the airway and the lungs are filled with room air. Carbon dioxide diffuses into the alveoli and equilibrates with the end-alveolar capillary blood (P_ACO_2 =$PcCO_2$ =$PaCO_2$ which is around 40 mm Hg). Each expired breath comes from two anatomical regions with no exact distinction of the transition. The first part comes from the anatomical dead space and is essentially unchanged from the inspired air. The second part arises at the level of the alveoli with concentration of CO_2 that reflect arterial CO_2 partial pressure, and concentration of O_2 that approaches the venous blood oxygen content. As exhalation continues, CO_2 concentration rises gradually and reaches a peak as the CO_2 rich gases from the alveoli make their way to the CO_2 sensor at the end of exhalation. The maximum CO_2 concentration is called end-tidal *CO_2* concentration. At the end of exhalation, the CO_2 concentration decreases to room air level (base line) as the patient commences inhalation of CO_2 free gases. When gases from both anatomical regions are mixed in the mixing chamber (mixed expired gas), the resulting fractional concentration of O_2 and CO_2 are volume mean i.e. it presents the volume of breath coupled with the Mixed Expired *CO_2* and O_2 concentrations.

1.4 Techniques for measuring gas concentrations

There are two commonly used techniques in measuring the O_2 and the CO_2 concentrations in expired breath. Both systems depend on the nitrogen balance technique. The two techniques are:

1- The Breath by Breath Technique: the breath by breath model, is based on simultaneous measurement of expired flow and expired gas concentrations *(FeO_2 and $FeCO_2$),* over small time interval (*dt*). The instantaneous volume of a composite gas is the concentration of this gas multiplied by the expired flow at the time interval (*dt*). The total volume of a composite gas in a breath is the summation of the instantaneous volumes added up over the entire breath. For an adult, with high flow and long

expiratory time, the volume contained in each time slot (dt) is relatively large, and the changes in values of expired gas concentrations are relatively slow. Therefore, small instrument measuring errors would not lead to large error in the final results. However, in the case of small and ill children with rapid respiratory rate and low tidal volume, this will affect the respiration pattern significantly and further decrease the accuracy of the system. Any failure to correctly detect and align the inspired volume with the corresponding gas concentrations can result in significant error. Also, the major problem with the breath by breath technique is the inaccuracy of the volume measurement of the breath (usually done by a mass flow sensor or a turbine whose range of accuracy is +/- 5% to 10% of full scale). Ventilation is assessed by measuring flow which is translated to volume. Very small breaths may not be detected and measured due to the low sensitivity of the mass flow sensor or the initial inertia of the turbine sensor. The breath by breath technique uses breath moving average and time-averaging to smooth data due to missing or irregular breathing. This smoothing technique may introduce errors in the final results.

2- The Mixing Chamber System: This system being investigated measures the instantaneous inspired ventilation ($\dot{V}i$) of the patient through a dry gas meter. The advantage of using the dry gas meter is its accuracy (+/- 1% accuracy for 10 liter sweep) regardless of the inspired flow (size and condition of child). Patient tidal volume (V_T) can vary from a small cystic fibrosis patient with V_T <300 ml to large 17 years old athletes whose V_T can exceed 3 liters at maximal exercise. Using a system of one way valves mouth piece, inspired gas is directed into the mouth from the dry gas meter and expired gas to a mixing chamber. The expired gases are captured in a variable volume mixing chamber so the values for O_2 and CO_2 concentrations are "physiologically" averaged. The mixing chamber volume can be adjusted according to the child estimate of the largest breath. This eliminates problems with variations in breath size among patients. The gas transport to the mixing chamber from the mouth requires time, which depends on the volume of the hoses and the mixing chamber. Based on the volume of the connecting hoses and chamber, the time delay between the mouth piece and the two gas analyzers reading the concentrations of O_2 *and* CO_2 is calculated. With this time delay, the

ventilation readings can be shifted (or corrected) in time to match the concentrations on the analyzers. For adults with large tidal volumes, (up to 3 liters), this time delay correction is very small as each breath will clear the connection tubing and most will arrive to the mixing chamber during expiration of that breath. However, for small children with lung disease and with tidal volumes of around 200 mL, this correction can be substantial. Without the time correction, the reported instantaneous values for $\dot{V}O_2$ *and* $\dot{V}CO_2$ will be lagged behind the actual O_2 consumption and CO_2 production of the body during the progressive test and this error will be proportional to the size and condition of the child.

A complex system that adapted the dry gas approach to measuring ventilation but used a breath by breath analysis has been described as a mean to accurately assess the transients at the start of exercise or a new workload (Davies et al., 1974). While such a system does incorporate lag time calculations, it is completely dependent on the rapid gas analytical facilities of a functioning respiratory gas mass spectrometer.

The system that is currently used in the Exercise Laboratory Department at the Hospital for Sick Children is built based on the mixing chamber technique with a dry gas meter. This technique offers higher accuracy and better system stability, especially for pediatric exercise testing. A mixing chamber system/dry gas meter is more complicated and bulkier than a breath by breath system; but this is a small price to pay for accuracy, particularly in a research setting.

When the system was developed, validation was done at steady state using a large number of trained subjects whose relationship between $\dot{V}O_2$ and work had been previously established. However, because there are no changes in the parameters being measured once steady state is achieved, it was not possible to test the lag time calculations and their effects under non steady state condition.

1.5 Hypothesis

The hypothesis is that defining the correction of the equipment time delay will result in greater accuracy in measuring $\dot{V}O_2$, and the effect of which would be greater in small children procedures. The aim of this work is to study and model the parameters affecting the time delay between the mouth piece and the O_2 and CO_2 sensors. The objective is to rerun the raw data from a variety of exercise tests that were conducted on a large number of children of various sizes, and calculate the differences in results that can be seen with and without the time delay correction factor. For a given sub-maximal exercise intensity, relationship between $\dot{V}O_2$ and workload is similar between all individuals with the same sex, weight, height, and age. This relationship will be used as reference to measure the improvement in the accuracy due to the time delay correction factor.

Chapter 2

2.1 Overview of the Exercise System

A mixing chamber based design exercise system was built and used for pediatric exercise testing procedures. The Exercise System was equipped with a dry gas meter, a cycle ergometer, a mouth piece, a patient circuit, a mixing chamber, O_2 and CO_2 analyzers, and a microcomputer based software to acquire, analyze and store patient data (Figure 2.1).

A calibrated cycle ergometer is used to apply workload to the patient during the exercise stages. The patient pedals on the cycle ergometer and breathes through a mouth piece that controls the flow directions of inspired and expired gases. The inspired ventilation volume ($\dot{V}_I$) is measured by a dry gas meter. The expired gas from the patient passes through an adjustable Plexiglas mixing chamber with a small fan, before a sample is drawn through out sensors for the measurement of mixed expired oxygen and carbon dioxide concentrations *(FeO_2, and $FeCO_2$).*

The Exercise System uses the Nitrogen Balance Technique to calculate the $\dot{V}O_2$ and $\dot{V}CO_2$ at a set workload. A computer data acquisition program acquires, records, processes, and displays the information gathered during a test procedure. The computer software also generates patient data reports to be used by physicians to assess the disease severity and progression.

The system is equipped with an O_2 and CO_2 manual calibrations assembly that uses a medically-certified calibrated gas tank with mixture of 14% O_2, 7% C O_2, complemented with N_2.

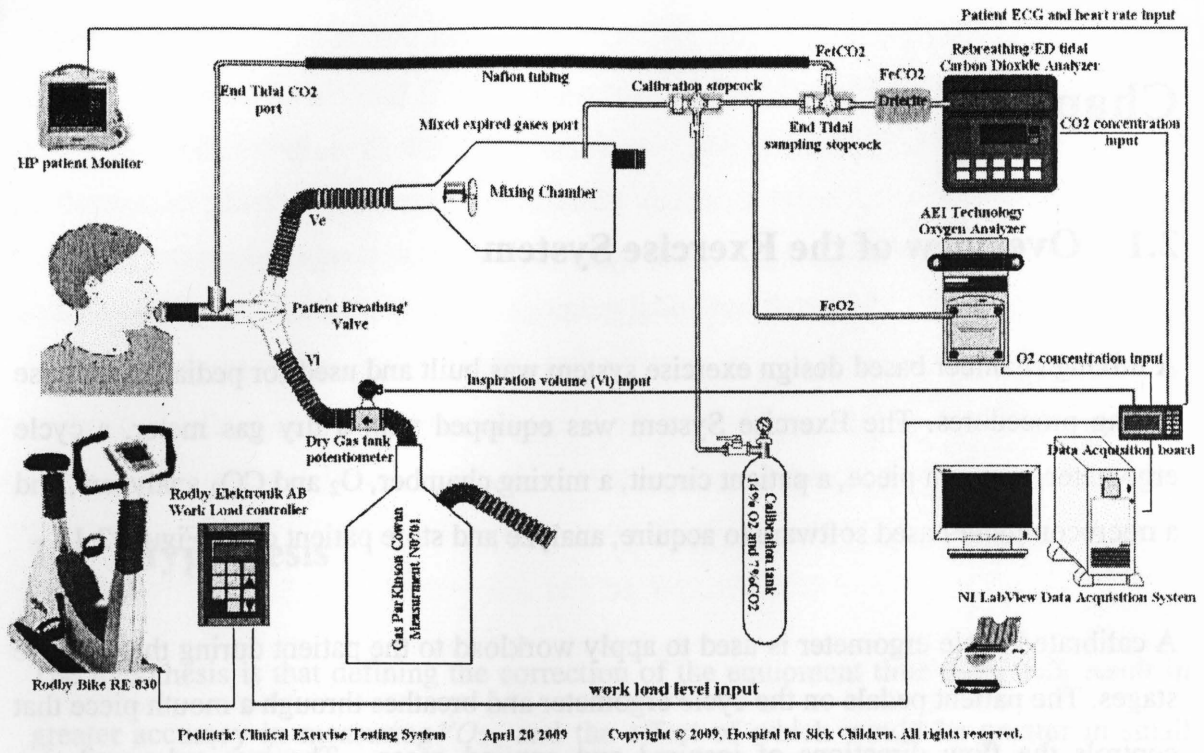


Figure 2.1: Block diagram of the Exercise System

2.2 Methodologies

2.2.1 Testing Protocols

Many protocols, combination of intensity and duration, have been advocated for exercise testing. Following are some of the popular testing protocols. A more detailed comparison and review is given by Arstila (1972).

The Bruce Protocol: This protocol is widely used for exercise"stress" testing for coronary artery disease (Bruce and McDonough, 1969).

The Balke Protocol: This protocol is carried out on a treadmill, but speed kept constant and the grade is increased from an initial zero grade by equal steps of 2.5 per cent every 1 minute (Nagle et al., 1965).

The "Scandinavian" Protocol: This protocol uses a cycle ergometer, with increment of power of 50 W for men and 33 W for women. Each step being maintained for 4 to 6 minutes (Atterhog et al., 1979).

The Jones Stage 1 Protocol: The test is performed on a cycle ergometer or treadmill. The power settings are standardized with the aim of obtaining a total duration for the test of 8 to 20 minutes (Buchfuhrer et al., 1983).

There are two advantages of the treadmill. One is that it is a form of exercise that is familiar to most subjects and the second is that more muscle mass is brought into play with this type of exercise than on a cycle ergometer. However, because external work depends on a number of factors ranging from body weight to speed and slope of the device, external work is rarely quantified. The cycle ergometer, on the other hand, allows easy measurement of external work and hence eases of use of normative data to compare to a subject's performance to that expected.

Clinical exercise testing needs and considerations will determine how an exercise test should be carried out, what measurements should be made, how to interpret the results, and what clinical use can be made of them. We will be using the Jones Stage 1 protocol (Jones, N. L. 1988), (Which may be used in most clinical situations, acceptable to most patients, short in duration, and consisting of a progressive incremental power test on a cycle ergometer). The exercise test is conducted to a symptom-limited or sign-limited maximum, and in which simple noninvasive measurements are made. The objective of this simple, economical procedure is to obtain measurements related to metabolic, cardiovascular, and respiratory adjustments as they evolve from the resting state to maximal exercise. Maximal exercise is defined as the point at which the patient is unable to continue because of exhaustion or, rarely, because safety limits have been reached. The Jones Stage 1 is a progressive incremental test where the workload is increased by a fixed incremental at the end of each minute with the size of the increment being chosen so exhaustion will occur between 5 to 10 minutes (Figure 2.2).

One disadvantage is that although steady state measurements are approached towards the end of each workload, the one minute increment is too short to achieve true steady state condition. However, such a compromise is well worth the simplification it brings to pediatric testing, especially if measurement errors due to equipment lag time can be minimized. With an incremental exercise test, there is a step function in work at each minute. During the minute previous to the change in work, the body approached a steady state condition where ventilation was just sufficient to remove the carbon dioxide produced by the exercising muscles and levels of carbon dioxide and oxygen in the blood stabilized. With the sudden change in work at the end of the minute, under greater load, the exercising muscles immediately extract more oxygen from the blood and produce more carbon dioxide.

As the levels of carbon dioxide in the blood go up and oxygen goes down, there is a rise in the mixed expired carbon dioxide produced at the lungs and a fall in the mixed expired oxygen. This will result in an increase in $\dot{V}O_2$ and $\dot{V}CO_2$. The higher levels of carbon dioxide in the blood stimulate ventilation which increases to where the levels of carbon dioxide and oxygen in the blood drop to previous values and begin to stabilize until the next incremental increase in work. There is a brief physiological time delay between the rise in carbon dioxide in the blood and the increase in ventilation and the subsequent fall in blood levels of carbon dioxide.

If there was no system lag time between the increase in mixed expired CO_2 concentration and decrease in mixed expired O2 concentration, the change in work load would result in a very rapid rise in $\dot{V}O_2$ and $\dot{V}CO_2$ which would reflect the true physiology. However, if there was a delay in the detection of the changes in expired gas concentration and the ventilation signal, which has no delay, and already increased at the time of detection, the calculation for $\dot{V}O_2$ and $\dot{V}CO_2$ would be erroneously high. This error in $\dot{V}O_2$ and $\dot{V}CO_2$ can be avoided if the signals from ventilation and mixed expired gases are aligned in time. The main purpose of this Stage 1 test is to study the functional capacity of the patients and relate their respiratory limitations to their disease progression.

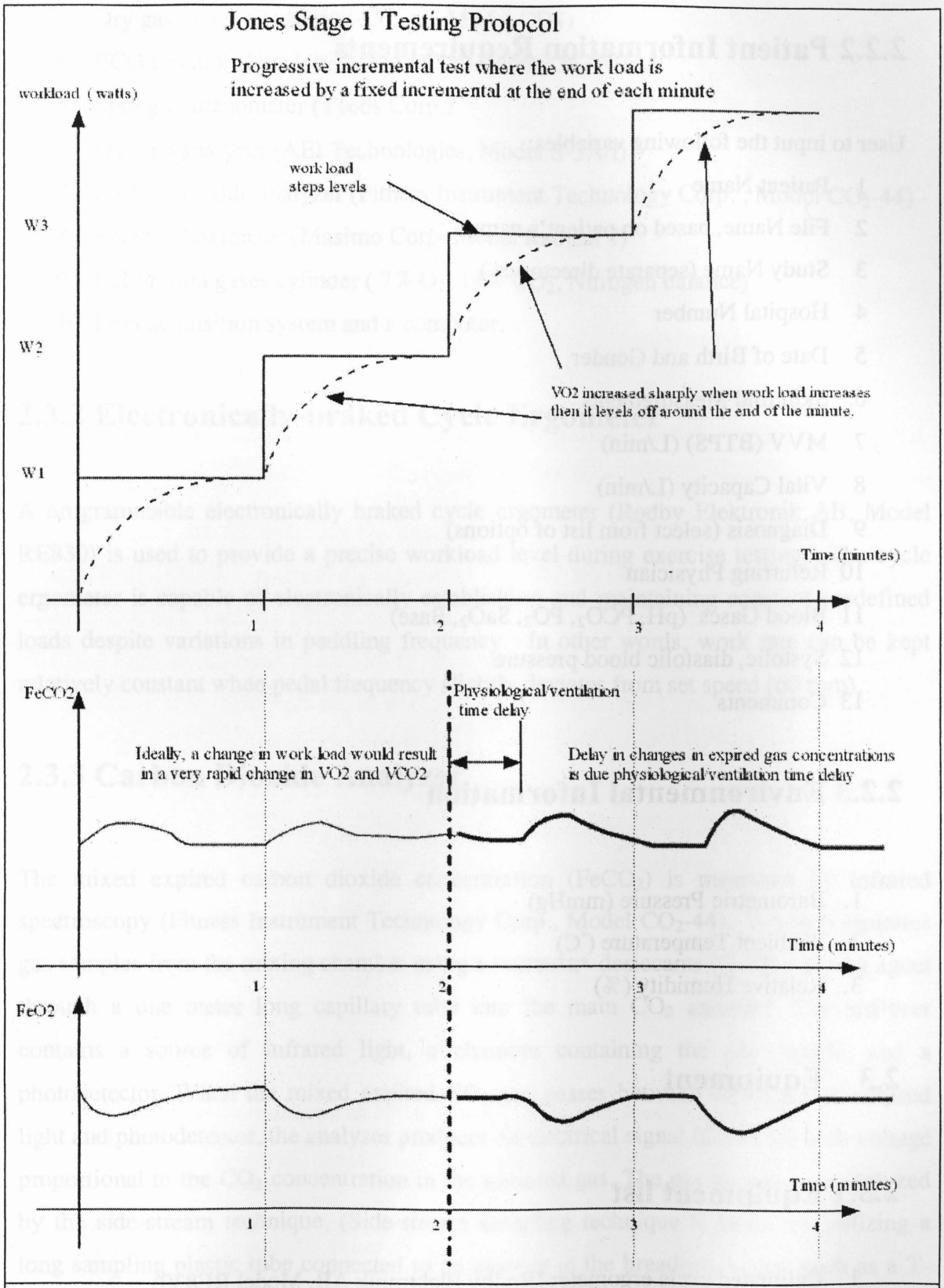


Figure 2.2: Relationship between workload, $\dot{V}O_2$, $FeCO_2$ and FeO_2

2.2.2 Patient Information Requirements

User to input the following variables:

1 Patient Name
2 File Name, based on patient's name
3 Study Name (separate directories)
4 Hospital Number
5 Date of Birth and Gender
6 Skin fold Measurements
7 MVV (BTPS) (L/min)
8 Vital Capacity (L/min)
9 Diagnosis (select from list of options)
10 Referring Physician
11 Blood Gases (pH, PCO_2, PO_2, SaO_2, Base)
12 Systolic, diastolic blood pressure
13 Comments

2.2.3 Environmental Information

1. Barometric Pressure (mmHg)
2. Ambient Temperature (°C)
3. Relative Humidity (%)

2.3 Equipment

2.3.1 Equipment list

1 Calibrated cycle ergometer (Rodby Elektronik AB, Model RE830)
2 Respiratory valves, tubing, nose clip

3 Dry gas meter (Parkinson-Cowan, Model CD4)
4 ECG monitor (Hewlett-Packard Corp. Model M1204A)
5 Sphygmomanometer (Tycos Corp.)
6 Oxygen analyzer (AEI Technologies, Model S-3A/I)
7 Carbon dioxide analyzer (Fitness Instrument Technology Corp. , Model CO_2-44)
8 Forehead oximeter (Masimo Corp. Model Radical 7)
9 Calibration gases cylinder (7% O_2, 14% CO_2, Nitrogen balance)
10 Data acquisition system and a computer.

2.3.2 Electronically-braked Cycle Ergometer

A programmable electronically braked cycle ergometer (Rodby Elektronik AB, Model RE830) is used to provide a precise workload level during exercise testing. The cycle ergometer is capable of electronically establishing and maintaining constant predefined loads despite variations in paddling frequency. In other words, work rate can be kept relatively constant when pedal frequency slightly deviates from set speed (60 rpm).

2.3.3 Carbon Dioxide Analyzer

The mixed expired carbon dioxide concentration ($FeCO_2$) is measured by infrared spectroscopy (Fitness Instrument Technology Corp., Model CO_2-44). A pump aspirates gas samples from the mixing chamber using a DRIERITE® desiccants ($CaSO_4$) drying agent through a one meter long capillary tube into the main CO_2 analyzer. The analyzer contains a source of infrared light, a chamber containing the gas sample, and a photodetector. When the mixed expired CO_2 gas passes between the beam of infrared light and photodetector, the analyzer produces an electrical signal (0-5VDC) with voltage proportional to the CO_2 concentration in the sampled gas. The gas samples are analyzed by the side-stream technique, (Side-stream sampling technique is based on utilizing a long sampling plastic tube connected to an adapter in the breathing circuit such as a T-piece at the endotracheal tube or mask connector. The sample gas is continuously

aspirated from the breathing circuit through the sampling tube and into the analyzer). The side-stream technique is applicable for spontaneously breathing non-intubated patients, but it requires constant aspiration of 100 cc to 300 cc of expired air/minute for analysis. In side-stream sensors, the temperature of the sampling gases may decrease during the passage from the patient to the analyzer, resulting in a decrease in the partial pressure of water vapor. Therefore, $FeCO_2$ measurements should be corrected for the effects of water vapor, in accordance with the type of analyzer used, and the manufacturer's instructions.

2.3.4 Oxygen Analyzer

The AEI Technology S-3A/I oxygen analyzer system is used to read out the O_2 concentration of the mixed expiratory gas in the mixing chamber. An R-1 flow control is used to control the flow of gas to be sampled by the S-3A/I system. The S-3A/I system provides continuous and accurate measurement of oxygen concentration from 0 to 100%. The analyzer consists of a readout/controller unit with a connecting cable to the O_2 sensor module. The single cell model N-22M O_2 sensor uses a durable solid oxide (stabilized zirconium) cell that has an inherently rapid response to changes in oxygen concentration and is maintenance free. A difference in oxygen partial pressure across the cell generates a DC voltage signal (0-10VDC) which is then fed to the data acquisition system for recording.

2.3.5 Dry Gas meter

The dry gas meter (Parkinson-Cowan, Model CD4) is used to measure dry gas (room air at room temperature) inspired volume ($\dot{V}_I$) in ml/minute. It offers so little resistance to the movement of air to the subject's lungs that it does not affect the subject's respiratory movements. The dry gas meter is made of a series of bellows that are connected with one way valves. As the bellows fill and empty, they turn a rod connected to a low inertia potentiometer. Each 10 liters increment of ventilation, the potentiometer

completes a full cycle. The output resistance of the potentiometer is proportional to the part of the cycle from 0 to 10 liters. Resistance of potentiometer increases with each inspiration until 10 liters is met at which point it resets to zero. The potentiometer is part of an electronic circuit where the output voltage signal increases during inspiration proportional to the size of the breath and stays constant during the expiration phase. The advantage of using the dry gas meter is its accurate (±1 % accuracy for 10 liter sweep).

2.3.6 Data Acquisition System

The Exercise System is equipped with 12 channels data acquisition systems (National Instrument, Model PCI 6035E), a PC (Pentium, 100 MHz, Win98) installed with Data Acquisition board (DAQ), and LabView software (LabView is a trademark of National Instrument Corporation, version 6.1). The DAQ boards are multi function plug-n-play, analog and digital input/output boards consisting of a onboard timer, 12 bit analog to digital converter (ADC) with 8 channel input, 2 digital to analog converters (DAC), and 24 TTL level logic inputs. The LabVIEW software offers direct control of all hardware on the DAQ board. The combination of a DAQ board and LabVIEW software makes a virtual instrument (vi). A vi can perform like an instrument and is programmable by the software with the advantage of flexibility of logging the data that is being measured. The system collects data in a continuous-acquisition mode and analyzes simultaneous high-speed inputs and then displays them in real time on computer screen as well as saving data on disks.

2.4 Testing Procedure

The equipment is set up and checked before the patient arrives to ensure that the procedure runs smoothly. The test is explained to the patient and the equipments described in order to reduce possible anxiety. The supervising physician obtains a brief history, concentrating on exercise related symptoms and any drugs that the patient may be taking. Anthropometric measurements (height, weight, and if required, skin fold

thickness) are made using standard techniques. With this information, the test protocol may be planned. The electrocardiograph electrodes are carefully placed and secured in a bipolar limb lead I configuration that will minimize noise from electrical activity from exercising muscles. A sphygmomanometer cuff is placed on the upper arm and taped in position. Forehead oximetry (Masimo Corp. Model Radical 7) is used to monitor patient arterial oxygen saturation. Forehead oximeter is secured and held in place with a headband. The light from LED in the oximeter probe is reflected off the skull and back to the adjacent receptor, passing only through non exercising vascular tissue, hence minimizing noise in the signal.

A cycle ergometer is used for the test; the patient is seated on the saddle and adjustments are made to ensure a comfortable cycling position. The knee should be almost fully extended at the bottom of the pedal stroke, the handlebars should be at waist height, and the mouthpiece and respiratory valve assembly are positioned so that the patient is leaning forward and has a comfortable neck position. The patient is then instructed to pedal without any added loads to obtain the necessary pedaling frequency (60 rpm) and to become accustomed to breathing through the valve. At this point the initial load is imposed. Load choice depends on patient size and condition. At the end of each minute the power is increased by an equal estimated amount so exhaustion occurs between 5 to 10 minutes. Subjects are instructed to maintain a pedal cadence around 60 rpm during exercise. During the last 15 seconds of each minute the blood pressure is recorded and instantaneous end-tidal CO_2 readings are sampled at the patient mouth piece. The patient is asked and monitored for any significant symptoms; communication is helped by showing a card to assess the patient's perceived exertion and the severity of symptoms such as chest pain. The test is continued to exhaustion or until the patient stops due to poor motivation. The observer may end the test for safety reasons at any time, for example, cardiac arrhythmia, extreme de-saturation, etc. Throughout the test the patient is encouraged to pedal steadily and regularly and is kept reassured and informed regarding progress in the test.

Chapter 3

3.1 Calculations

The fundamentals of the exercise laboratory system are to be able to measure O_2 consumption $(\dot{V}O_2)$ and CO_2 production $(\dot{V}CO_2)$ during a known rate of work in pediatric population. The inspiration Volume $\dot{V}_i$ is measured by the dry gas tank meter. The workload is set by the workload controller of the cycle ergometer. The O_2 and CO_2 concentrations are measured by their respective analyzers. These variables constitute the raw data being measured in real time. From these direct raw measurements, $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_e$, and R are calculated and provided in real time by interfacing electronic gas analyzers, a dry gas meter, and cycle ergometer controller to a data acquisition system that processes, presents and displays data on computer screen.

3.2 Measuring Inspired Ventilation ($\dot{V}_i$)

Dry gas meters are very accurate over the 10 liters sweep, but less accurate within the rotation. The calculation of $\dot{V}_i$ will be done at the end of each complete rotation of the dry gas meter rather than at a timed interval. To measure the tidal volume, the number of breaths per rotation will be counted and divided by the volume of the dry gas meter sweep (10 liters). It is recognized that this will give rise to errors with partial breaths, but this will only be a significant issue in large subjects with high tidal volumes. In this situation, meaning the tidal volumes of two or more adjacent sweeps would improve accuracy if this was to be necessary.

3.3 Standardizing Gas Volumes

The volume of a gas varies depending on its temperature, pressure, and content of water vapor, even though the absolute number of gas molecules remains constant. These three

factors must be considered when gas volumes are compared under different environmental conditions and used subsequently in metabolic and physiologic calculations. The volume of a gas varies directly with temperature. Increasing the temperature causes the volume to increase proportionately (*Charles' Law*) (Jones, N. L. 1988). The volume of a gas varies inversely with pressure. Increasing the pressure on a gas causes the volume to decrease in proportion to the increase in pressure (*Boyle's Law*) (Jones, N. L. 1988). Convention has $\dot{V}O_2$ and $\dot{V}CO_2$ expressed as standard temperature and pressure dry. The volume of a gas varies depending on its water vapor content. The volume of a gas is greater when the gas is saturated with water vapor than it is when the same gas is dry (i.e., contains no moisture). The conventional standards that provide the frame of reference for expressing a volume of gas are either STPD ($\dot{V}O_2$ *and* $\dot{V}CO_2$) or BTPS ($\dot{V}e$).

Two values for ventilation are derived. The first represent the volume changes in the lungs during breathing, and it is calculated for the conditions that exist in the lung, i.e., at body temperature (37°C) and ambient pressure and saturated with water vapor *(BTPS).* The second is used to calculate the quantities of oxygen and carbon dioxide exchanged, in L/min, and because these represent metabolic equivalents, they are calculated at standard temperature (0°C), pressure (760 mmHg), and dry. The use of BTPS for $\dot{V}_e$ and STPD for $\dot{V}O_2$ and $\dot{V}CO_2$ are by convention.

$\dot{V}_e$ is conventionally expressed in BTPS. To calculate $\dot{V}_e$ *(BTPS)* from $\dot{V}_e$ *(ATPS),* we need to know, additionally, the ambient temperature *(T_A C°)* and pressure *(P_B mmHg),* and the ambient humidity (%). Ambient temperature in °C is converted to temperature (°K) by adding 273.

The percentage humidity is converted to ambient water vapor pressure *(PH_2O, A)* by fractional multiplication of the saturated water vapor pressure at the ambient temperature obtained from a table or an equation. Water vapor has a partial pressure of 47 mmHg at 37°C.

$$\dot{V}e_{BTPS} = \dot{V}e_{ATPS}\left(\frac{273^{\circ}K + 37}{273^{\circ}K + T_A\,^{\circ}C}\right) * \left(\frac{P_B - PH_2O}{P_B - 47}\right) \quad \text{..... (Equation 1)}$$

In all metabolic calculations, gas volumes are always expressed as STPD. $\dot{V}_i$ and $\dot{V}_e$ must be expressed in STPD in order to be used in calculating $\dot{V}O_2$ *and* $\dot{V}CO_2$. To calculate $\dot{V}_i$ *(STPD)* and $\dot{V}_e$ *(STPD),* the following equations are used:

$$\dot{V}i_{STPD} = \dot{V}i_{ATPS}\left(\frac{273^{\circ}K}{273^{\circ}K + T_A\,^{\circ}C}\right) * \left(\frac{P_B - PH_2O}{760}\right) \quad \text{..... (Equation 2)}$$

$$\dot{V}e_{STPD} = \dot{V}e_{ATPS}\left(\frac{273^{\circ}K}{273^{\circ}K + T_A\,^{\circ}C}\right) * \left(\frac{P_B - PH_2O}{760}\right) \quad \text{..... (Equation 3)}$$

P_B =Ambient barometric pressure

Barometric pressure at sea level =760 mmHg

3.4 Calculating Expired Ventilation $\dot{V}_e$

Because O_2 intake and CO_2 output will be calculated in this stage, we need to know both expired and inspired ventilation in this test. The inspired ventilation $\dot{V}_i$ has been measure by the dry gas meter. The expired ventilation $\dot{V}_e$ is calculated based on the nitrogen balance technique where nitrogen is treated as an inert gas and the amount of nitrogen entering the body is equal with that leaving. Argon in the inspired air is treated as nitrogen since both are inert gases in this context. Because $\dot{V}_i$ and $\dot{V}_e$ are influenced by temperature and pressure, these gas volumes must be standardized to reference condition STPD.

$$\dot{V}e_{ATPS} * FeN_2 = \dot{V}i_{ATPS} * FiN_2$$

$$\dot{V}e_{ATPS} = \frac{\dot{V}i_{ATPS} * FiN_2}{FeN_2} \quad \text{..... (Equation 4)}$$

FiN_2 and FeN_2 are obtained by subtracting the sum of inspired O_2 and CO_2 concentration and expired O_2 and CO_2 concentrations, respectively, from 1. O_2 fraction of the inspired air is FiO_2 =0.209. CO_2 fraction of the inspired air is $FiCO_2$= *0.0003.*

$FiN_2 = 1 - (FiO_2 + FiCO_2) = 1 - (0.209 + 0.0003) = 0.7904$ ..... (Equation 5)

$FeN_2 = 1 - (FeO_2 + FeCO_2)$ ..... (Equation 6)

Now we can calculate *Ve:*

$$\dot{V}e_{ATPS} = \frac{\dot{V}i_{ATPS} * 0.79}{1-(FeO_2 + FeCO_2)} \quad \text{..... (Equation 7)}$$

$\dot{V}_e$ and $\dot{V}_i$ must be converted to (STPD) so they can be used to calculate $\dot{V}O_2$ *and* $\dot{V}CO_2$. $\dot{V}_e$ and $\dot{V}_i$ are converted from *(ATPS) to (STPD)* using equation 2 and equation 3 respectively.

All the parameters are known. FeO_2 and $FeCO_2$ are measured by the analyzers. $\dot{V}_i$ is measured by the dry gas meter.

3.5 Calculating VO_2

$\dot{V}O_2$ is the difference between the volume of O_2 inspired per minute and the volume of O_2 expired per minute.

$$\dot{V}O_2 = \dot{V}O_{2\,inspired} - \dot{V}O_{2\ \text{exp ired}}$$

$$\dot{V}O_2 = (\dot{V}i_{STPD} * FiO_2) - (\dot{V}e_{STPD} * FeO_2) \quad \text{..... (Equation 8)}$$

3.6 Calculating VCO_2

$\dot{V}CO_2$ is the difference between the volume of CO_2 expired per minute and the volume of CO_2 inspired per minute.

$$\dot{V}CO_2 = \dot{V}CO_{2\ \text{exp ired}} - \dot{V}CO_{2\,inspired}$$

$$\dot{V}CO_2 = (\dot{V}e * FeCO_2) - (\dot{V}i * FiCO_2)$$

$$\dot{V}CO_2 = (\dot{V}e * FeCO_2) - (\dot{V}i * 0.0004)$$, the second term is usually ignored.

$$\dot{V}CO_2 = \dot{V}e_{STPD} * FeCO_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 9)}$$

3.7 Calculating the respiratory exchange ratio (R)

$$R = \frac{VCO_2}{VO_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 10)}$$

The Respiratory Ratio (R) is the ratio of carbon dioxide production to oxygen consumption.

3.8 Lag Time

3.8.1 Lag Time Algorithm abbreviations

V_A =Apparatus dead space, the volume of expire tubing from the valve to the mixing chamber (0.690 liters).

Vm =mixing chamber volume (liters)

V_0 =residual volume at start of sweep (liters)

V_1 =volume of first breath (liters)

V_2 =volume of second breath (liters)

V_n =volume of n^{th} breath (liters)

$Vn_{+1} - Vn$ =tidal volume of n^{th} breath (liters).

FVC =Forced Vital Capacity (liters)

t_1 =the start of the first breath (seconds)

t_2 =the start of the second breath (seconds)

t_{D1} =First breath total lag time (seconds)

t_{AD} =apparatus time delay (due to sampling tube and response time of analyzers, which is 15 seconds).

3.8.2 Lag Time Algorithm

Because the valve deadspace and the tubing on the expiratory limb have a significant volume, the time base signal for mixed expired gases will reflect concentrations of gas that lag behind the instantaneous measured inspired ventilation signal. This will be less with large subjects at high workloads since their tidal volume may be sufficient to clear the deadspace and tubing in a single breath. However, the lag time will be largest in small subjects with low workloads where the lag time may be in the order of several breaths. The overall lag time will be compounded by the length of time required for the expired gas sample at the exit of the mixing chamber to reach the analyzers and have its concentration measured (Apparatus Delay, t_{AD}).

Since the patient tidal volume and the apparatus deadspace (valve plus expiratory tubing volume) are known, it is possible to calculate the time the expired gas will arrive at the mixing chamber and be analyzed relative to the immediate ventilation signal which occurs in real-time. With the lag time, the inspired ventilation can be shifted in time so that it corresponds to the mixed expired gases for that epoch. If there is a fan in the mixing chamber and the volume is approximately 1.5 times the maximal possible tidal volume ($Vm = 1.5 * Maximal\,Tidal\,Volume$), the mixing within the chamber can be considered instantaneous. The maximal tidal volume of the patient is determined by Forced Vital Capacity (FVC) measured by spirometry in the Pulmonary Function Laboratory Department.

It would be extremely unusual for a maximal tidal volume to reach more than 70% of the FVC except in severe disease. Hence the mixing chamber volume is the FVC.

Apparatus Delay (t_{AD}) is the other time delay which is due to the sampling tube and response time of gas analyzers.

The lag time algorithm (Figure 3.1) sums consecutive expired volumes (actually taken from the previous inspiration read off the dry gas meter) until the volumes of the added breaths exceed the apparatus dead space (e.g. the volume of the expired tubing at the mouth piece plus half the volume of the mixing chamber). Then the lag time is defined as the time from the start of the first expiration (t_0) to that of the breath where the sum exceeded the apparatus dead space. Hence, moving down the breaths, a lag time is calculated for each full breath during the cycle of the dry gas meter. Partial breaths are ignored for the purpose of lag time (although they are taken into consideration for the purpose of calculating inspired ventilation $\dot{V}_i$).

The total lag time of the system equal to lag time due to breathing circuit dead space plus apparatus delay time.

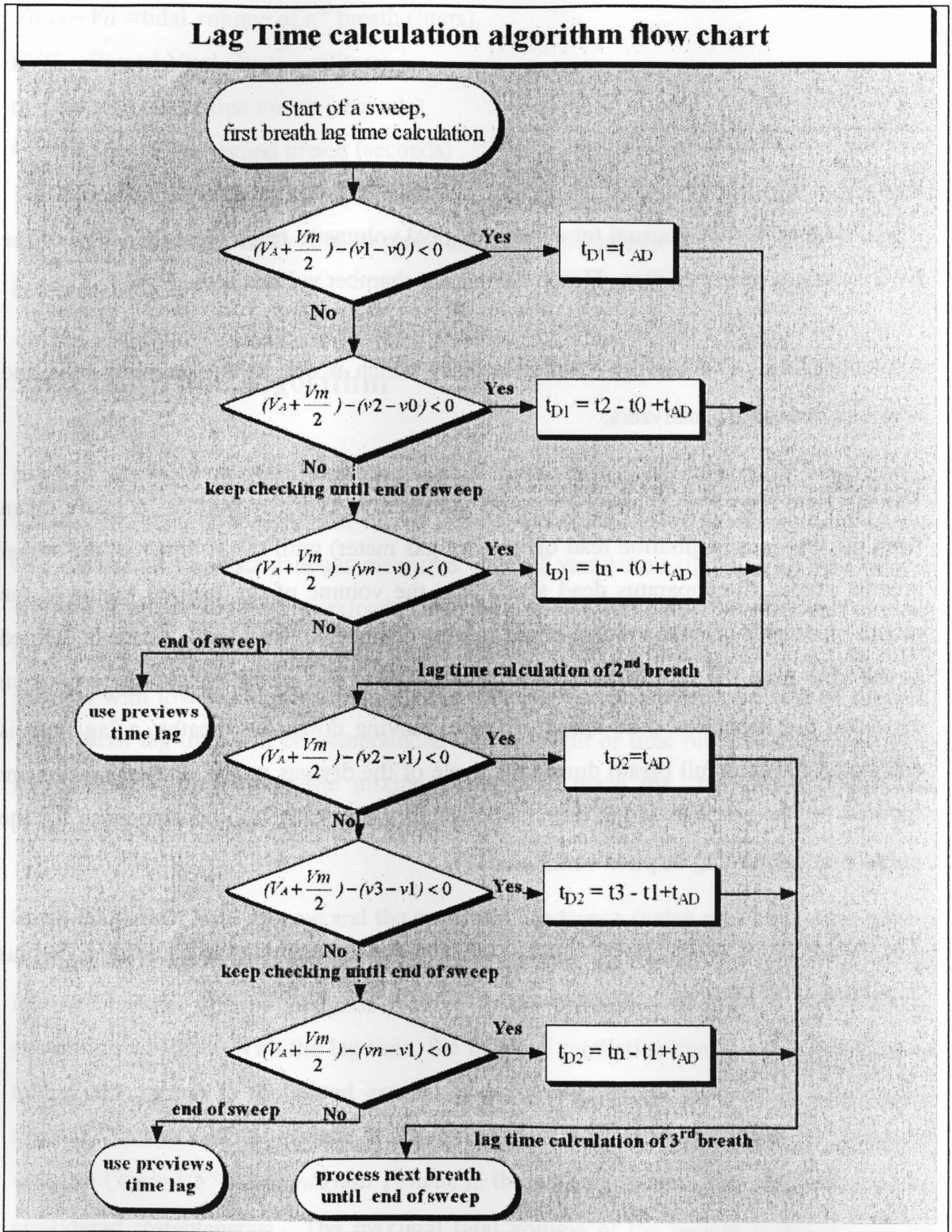


Figure 3.1: Lag time algorithm flow chart

3.8.3 Graphical explanation of lag time

The criteria to define the time lag for an arbitrary breath is when the volume of that breath or the accumulative sum of multiple consecutive breaths, exceeds the total volumes of the dead space plus half of the mixing chamber volume.

For example, if V_0 is the volume of the partial breath in a sweep (usually ignored in calculation) and if it takes 2 breaths (V_1=volume of first breath and V_2 =the volume of second breath) to clear the dead space of the breathing circuit, the criteria to determine the time delay of the first breath is when $(V_2 - V_0) > \left(V_A + \frac{Vm}{2}\right)$.

In another word $\left(V_A + \frac{Vm}{2}\right) - (V_2 - V_0) < 0$, see (Figure 3.2)

The time lag for the first breath is defined as the time from the start of the first breath (t_0) to the time (t_2) that of second breath that fulfills the above criteria. The first breath lag time $= t_2 - t_0$. Analyzer sampling delay time t_{AD} is also added to the total lag time for the first breath $t_{D1} = (t_2 - t_0) + t_{AD}$. Please see Lag Time flowchart in Figure 3.1.

Note that during inspiration, no gas enters the mixing chamber so gas concentration remains constant.

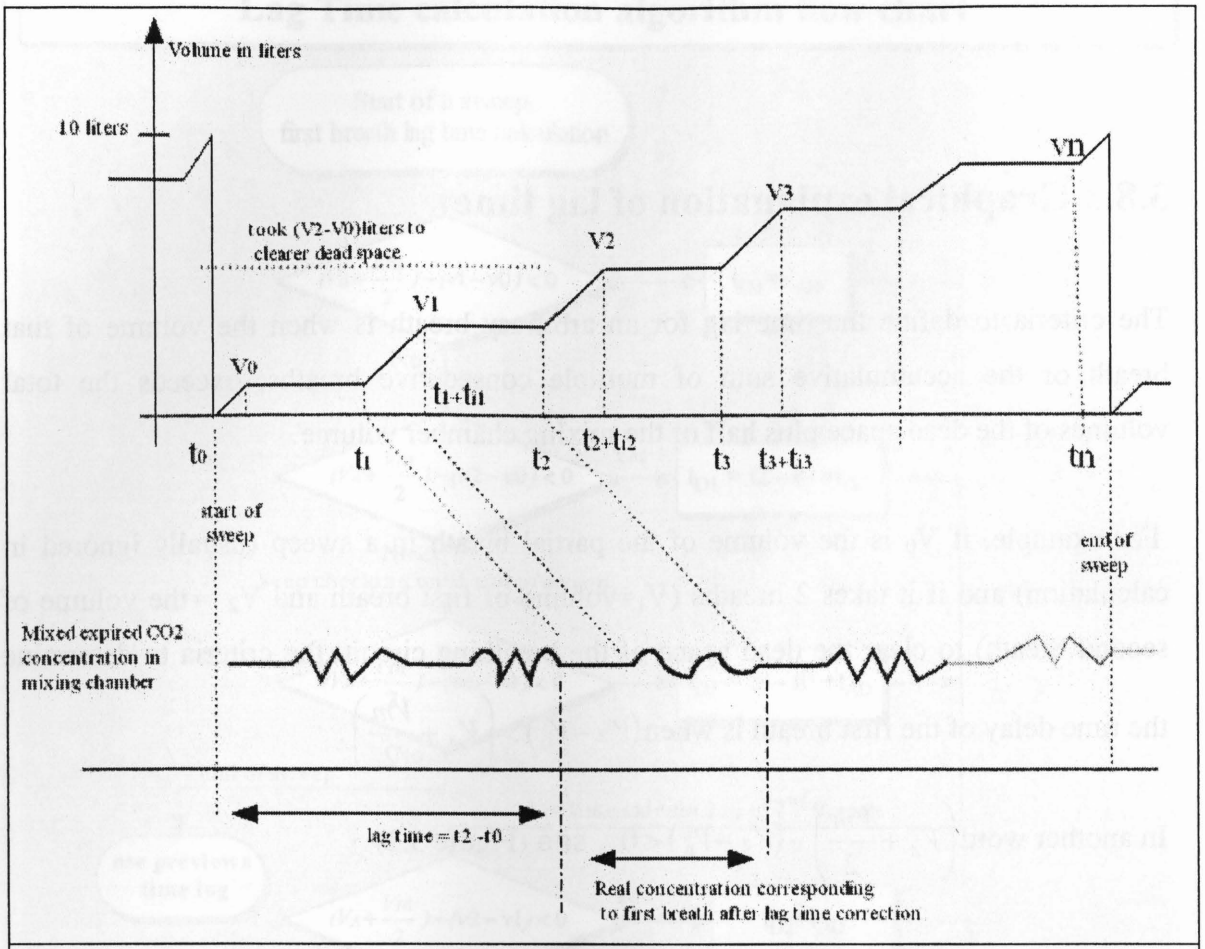


Figure 3.2: Lag time correction diagram

3.8.4 Measuring algorithm of O_2 and CO_2 concentrations

When gases from both anatomical regions are mixed in the mixing chamber (mixed expired gas), the resulting fractional concentration of O_2 and CO_2 are volume mean i.e. it presents the volume of breath coupled with the mixed expired O_2 and CO_2 concentrations.

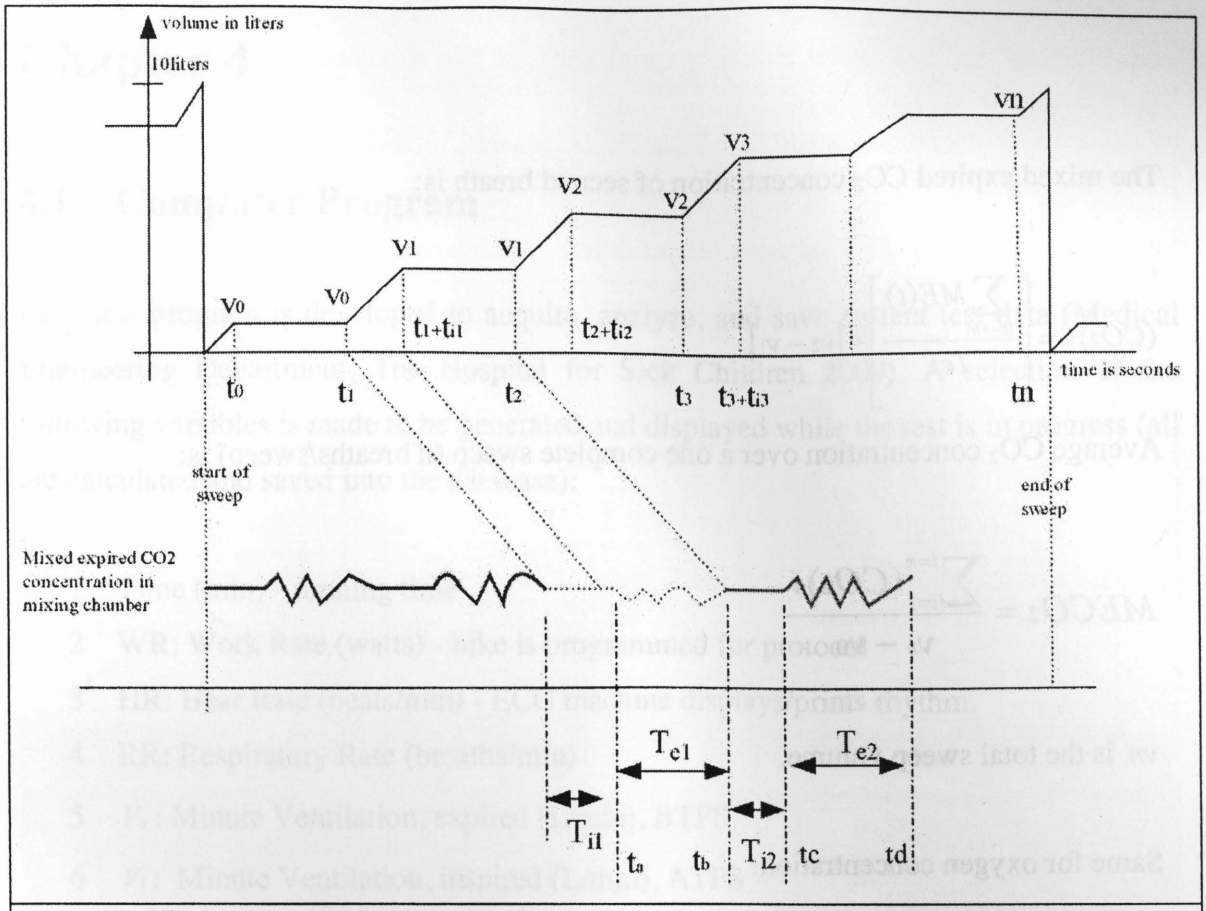


Figure 3.3: Measuring algorithm of the O_2 and the CO_2 concentrations

Referring to Figure 3.3, the mixed expired CO_2 concentration of first breath $(v_1 - v_0)$ in a sweep is:

$$(CO_2)_1 = \left[\frac{\sum_{ta \to tb} ME(t)}{Te_1} \right] * [v_1 - v_0]$$

$(v_1 - v_0)$ is the breath volume. $ME(t)$ is the time average of the mixed expired CO_2 concentration measured at the mixing chamber during the expiration period Te_1, between ta and tb . (Te =expired breath time only in seconds).

The mixed expired CO_2 concentration of second breath is:

$$(CO_2)_2 = \left[\frac{\sum_{tc \to td} ME(t)}{Te_2} \right] * [v_2 - v_1]$$

Average CO_2 concentration over a one complete sweep (n breaths/sweep) is:

$$MECO_2 = \frac{\sum_{i=1}^{i=n} (CO_2)\, i}{v_n - v_0}$$

vn is the total sweep volume.

Same for oxygen concentration:

$$(O_2)_1 = \left[\frac{\sum_{ta \to tb} (20.93 - MEO2(t))}{Te_1} \right] * [v_1 - v_0]$$

$$(O_2)_2 = \left[\frac{\sum_{tc \to td} (20.93 - MEO2(t))}{Te_2} \right] * [v_2 - v_1]$$

$$MEO_2 = 20.93 - \left[\frac{\sum_{i=1}^{i=n} (O_2)\, i}{v_n - v_0} \right]$$

The composition of inspired air remains relatively constant (CO_2 =0.03%, O_2 =20.93%, N_2 =79.04%).

Chapter 4

4.1 Computer Program

LabView program is developed to acquire, analyze, and save patient test data (Medical Engineering Department, The Hospital for Sick Children 2009). A selection of the following variables is made to be generated and displayed while the test is in progress (all are calculated and saved into the database):

1 Time (min) - running time
2 WR: Work Rate (watts) - bike is programmed for protocol
3 HR: Hear Rate (beats/min) - ECG machine displays/prints rhythm.
4 RR: Respiratory Rate (breaths/min)
5 $\dot{V}_e$: Minute Ventilation, expired (L/min), BTPS
6 $\dot{V}_i$: Minute Ventilation, inspired (L/min), ATPS
7 V_T: Tidal Volume (ml), BTPS
8 Ve/MVV: Respiratory Reserve (%), BTPS
9 SaO_2: Saturation (%)
10 FeO_2: Mixed expired oxygen
11 $FeCO_2$: Mixed expired carbon dioxide
12 $\dot{V}O_2$: Oxygen consumption, absolute (L/min), STPD
13 $\dot{V}O_2$: Oxygen consumption, normalized ($ml.kg^{-1}.min^{-1}$), STPD
14 $\dot{V}CO_2$: Carbon dioxide production, absolute (L/min), STPD
15 $\dot{V}CO_2$: Carbon dioxide production, normalized ($ml.kg^{-1}.min^{-1}$), STPD
16 R: Respiratory Exchange Ratio ($\dot{V}CO_2 / \dot{V}O_2$)
17 O_2 Pulse: (ml $\dot{V}O_2$ /heart beat)

Figure 4.1 shows the flow diagram of the LabView program. Users navigate and select their test procedures according to their needs. Some of the tests (such as Stage II

equilibrium test and Stage II Exponential test) are not discussed in this paper because these tests are out of our scope.

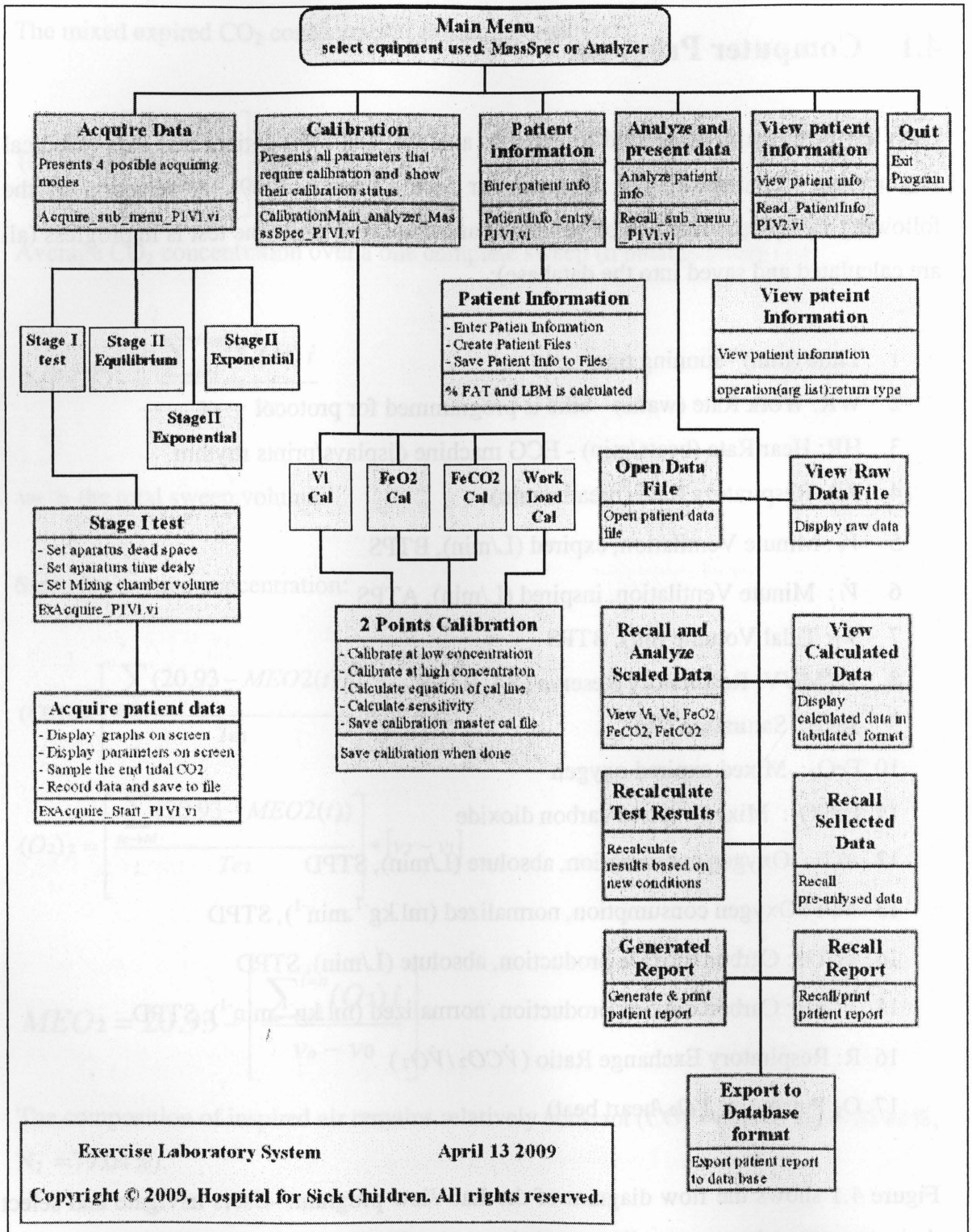


Figure 4.1: LabView Computer Data Acquisition Program Flow Diagram

A typical test will start with entering the patient demographic information and the environmental parameters. After that, calibration procedures are performed to calibrate measuring equipments. Then the test protocol is selected and the patient test is performed. Patient information and test results are stored in a series of files in the patient directory.

The patient files includes: patient information file (.pin), test comment file (.doc), calibration file (.cal), raw data file (.raw), scaled data file (.sca), sweep file (.swp), analyzed file (.ana), debug file (.bug), and report files (.rpt). Figure 4.2 shows the LabView Stage1 acquiring screen shot. Also The LabView program allows user to generate, save, and print reports.

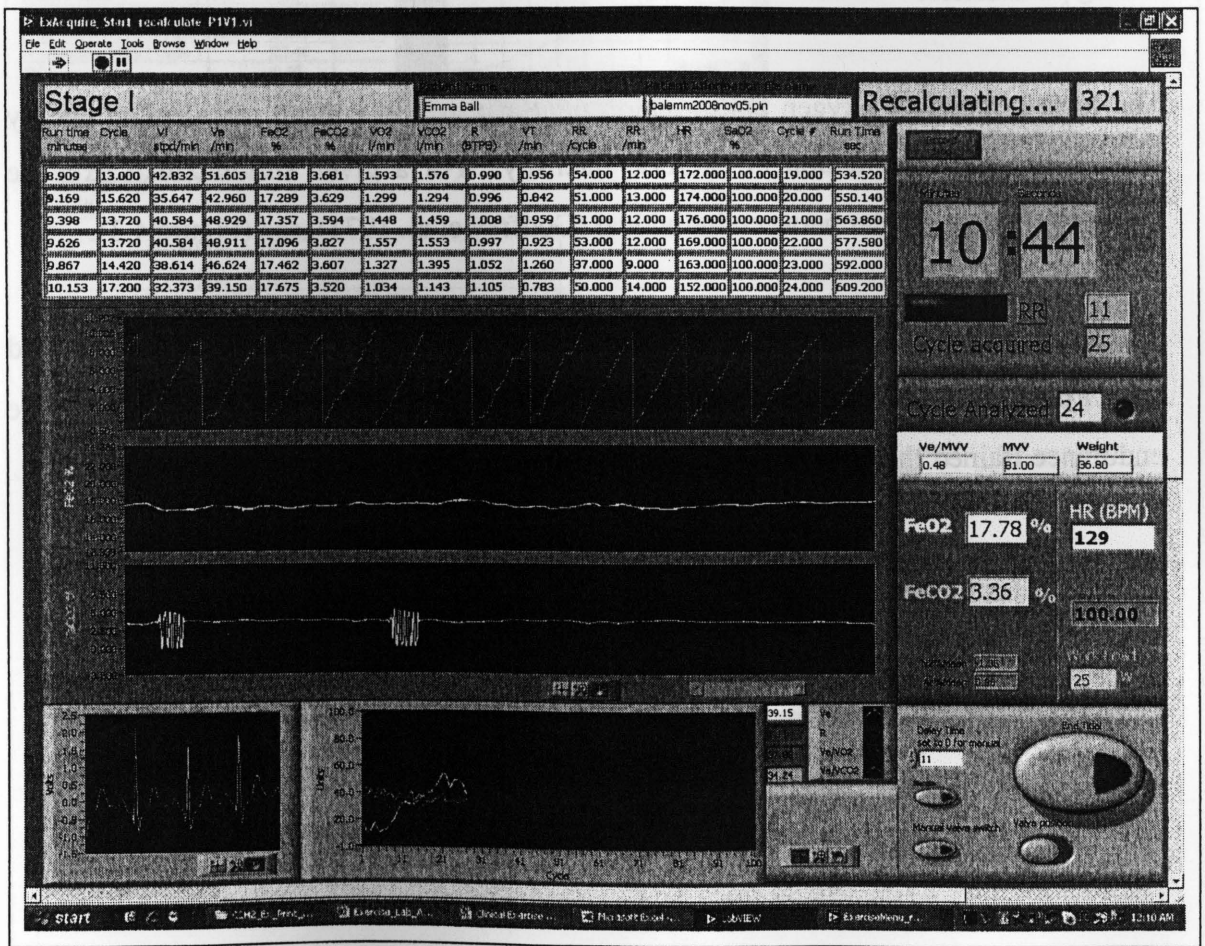


Figure 4.2: LabView Stage1 acquiring screen shot

4.2 Patient Report

LabView program is capable of generating and printing patient reports (Figure 4.3). Patient report includes patient information, test data, comments, and graphs for several testing parameters.

The measurement of oxygen consumption ($\dot{V}O_2$) provides a mean to calculate energy expenditure and information of exercise intensity. For a given sub-maximal exercise intensity, $\dot{V}O_2$ is similar between individual (Godfrey et al. 1971), see (Figure 4.3).

As exercise intensity increases, $\dot{V}O_2$ increases linearly over the range between rest and near $\dot{V}O_{2\,max}$. During sub-maximal exercise, individuals have similar $\dot{V}O_2$. The more endurance trained the individual, the higher will be the intensity at $\dot{V}O_{2\,max}$ (Jones, N. L. 1988)

SickKids
THE HOSPITAL FOR SICK CHILDREN

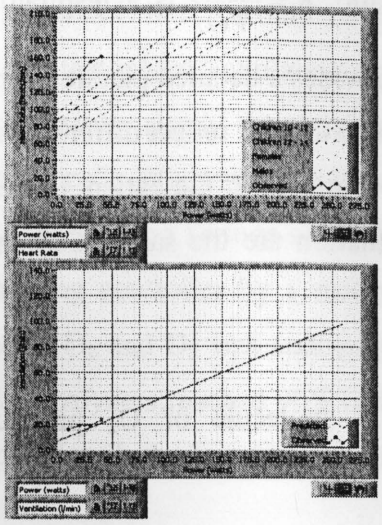
Respiratory Medicine Exercise Laboratory

Name	Patient Full Name
MRN #	123456
Date of birth	2000,October,01
Age	8
Sex	f
Exercise Test	Stage I
Date of Test	2009,March,18
Referring Physician	CF Clinic

Diagnosis
CF

Weight	kg	133
Height	cm	27.6
B. S. A.	Sq. m	1.02
Fat	%	21
L. B. M.	kg	21.9

FVC	1.83
FVC % Pred.	92
FEV1	1.63
FEV1 % Pred.	97
FEV1 / FVC	0.89
MVV	69
MVV % Pred.	106



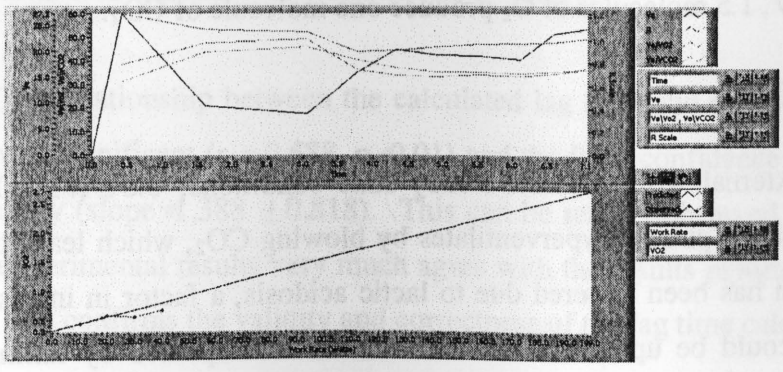
		1st WR	Peak WR
WR	(% pred.)		50
SaO2	(%)	99	100
PetCO2	(mmHg)	38.74	36.51
Tidal Volume	(ml)	606	730
Heart Rate	(beats/min)		161
VO2 STPD	(ml/kg/min)	15.88	24.55
Ventilation BTPS	(l/min)		23.40
RQ			0.98
BP	(mmHg)	100/70	100/70
VD/VT		0.20	0.10

* Indicates abnormal

Test Termination
Leg Fatigue
BP Changes
Other

Physician's Comments

Power	(Watts)	10	20	30	40
SaO2	(%)	99	100	100	100
PetCO2	(mmHg)	38.74	38.24	41.78	36.51
Tidal Volume	(ml)	606	708	706	730
Heart Rate	(beats/min)	129	138	155	161
VO2	(l/min)	0.44	0.58	0.56	0.68
VCO2	(l/min)	0.39	0.54	0.54	0.66
Ventilation BTPS	(l/min)	16	19	19	23
RQ		0.89	0.94	0.96	0.98
BP	mmHg	100/70			100/70
VD/VT		0.20	0.13	0.20	0.10



Technician's Comments
First bike test and was very submax effort. Pedaling frequency irregular and mouthpiece seal inconsistent. Legs were limiting factor at end of test.

Figure 4.3: Patient Report

Chapter 5

5.1 Quality Control

The Respiratory Exchange Ratio $R = \frac{VCO_2}{VO_2}$ is a respiratory indicator in a Pulmonary Function Laboratory test. R provides a detailed picture of the body's metabolic processes at a known rate of work. R can be used to reflect different proportion of carbohydrate and lipid substrates used in the metabolism. If the patient is metabolizing only carbohydrate, the inspired and expired ventilation are the same. Carbohydrate structures are mainly carbon and water (CH_2O).

$O_2 + CH_2O \rightarrow CO_2 + H_2O$, 1 molecule of O_2 produces one molecule of CO2.

$$R = \frac{1 \ \ molecule\ of\ CO_2}{1 \ \ molecule\ of\ O_2} \cong 1$$

If fat is being metabolized, then inspired ventilation is greater than expired ventilation. Saturated fat structures are long lines of $-CH_2-CH_2-$ followed by an acid ending. Since water vapor content in expired gas is proportional only to temperature, not H_2O production, H_2O is not quantified as respirable gas.

$1\frac{1}{2}O_2 + CH_2 \rightarrow CO_2 + H_2O$, 1.5 molecules of O_2 produce one molecule of CO_2.

$$R = \frac{1 \ \ molecule\ of\ CO_2}{1.5 \ \ molecules\ of\ O_2} \cong 0.7$$

$\dot{V}O_2$ is tightly related to external work. Under steady state conditions, $0.8 \leq R \leq 1.0$. For non steady state conditions, patient hyperventilates by blowing CO_2, which leads to increase in blood pH which has been lowered due to lactic acidosis, a factor in intense exercise. In this case R could be up to 1.2 but this will be accompanied by falling $FetCO_2$. This physiological constraint can be used for quality assurance. Respiratory exchange ratios below 0.8 and above 1.2 call for an examination of gas calibration curves and analysis.

5.2 Validation of the Lag Time calculation

A Harvard Animal Ventilator was used to mimic patient ventilation. It was recognized that this ventilatory pattern of the mechanic device was constant where as there would be variations in patient breathing which likely would be greatest at the start and end of exercise so only sections of the test where ventilation appeared relatively constant were used. The tidal volume and respiratory rate of the patient were set on the ventilator which was connected to the "mouth piece". Where tidal volumes greater than that possible for the ventilator where needed, a calibration syringe set at the appropriate tidal volume was operated manually with breathing controller by a metronome. At a port at the mouth piece, a gas with an increased CO_2 and O_2 was suddenly connected at the mouth piece. The time until the CO_2 and O_2 analyzers reached 90% of their new value was recorded as the lag time. This was compared with the lag time calculated by the Lab View program during the actual test.

Linear regression was performed on all calculated and measured lag time data points. Regression equation for all data points is $Y = 1.3886X - 8.3181$

Pearson product moment correlation coefficient for the data sets of calculated and measured lag time was calculated to $r = 0.688$.

The relationship between the calculated lag time and the experimentally found lag time was significant ($r = 0.688$, $p < 0.01$) and the 95% confidence interval of the slope overlap unity (slope $= 1.388 \pm 0.818$). This can be readily observed in (Figure 5.1) in which the experimental results very much agree with the results reported by the LabView program. This confirms the validity and correctness of the lag time calculation algorithm.

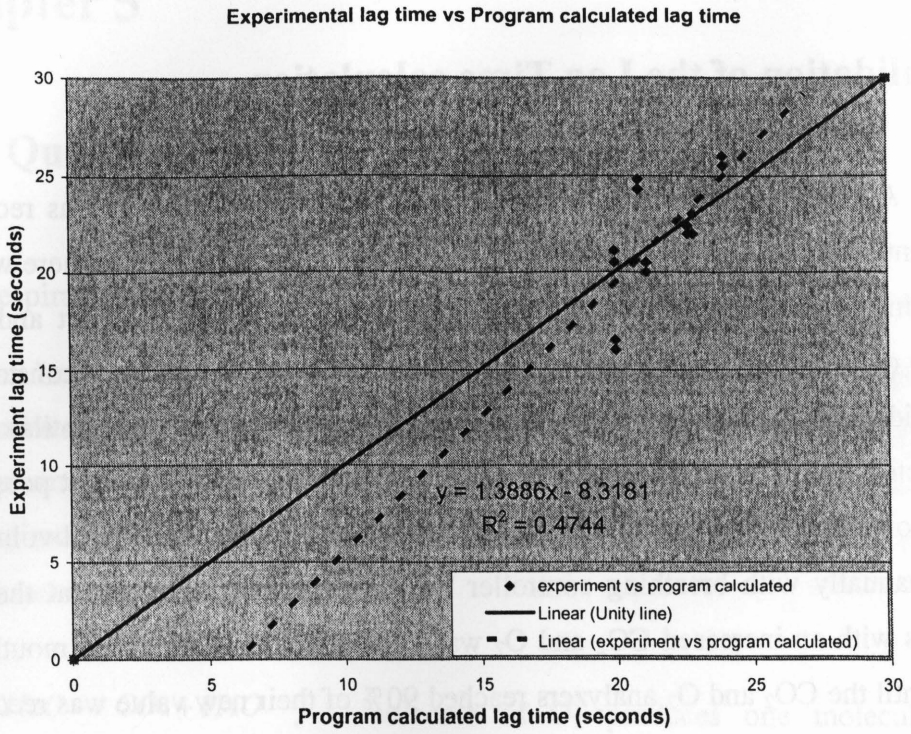


Figure 5.1 Experimental lag time versus lag time reported by LabView Program

5.3 Statistics

Direct or invasive measurements of exercise testing parameters are ethically impossible. The true values remain unknown in anything other than extremely well controlled steady state testing. A new method has to be evaluated based on theory behind the exercise test as well as quality assurance experimental tests. If the new method experimental results agree sufficiently well with what is expected, then this method can be accepted. Statistical method can be used to help analyze the experimental test results and produce statistical data that measure the level of confidence that this method comply with expected results. The Bland-Altman (Bland JM, Altman DG. 1986) limit of agreement analysis method is used here to graphically describe the distribution of the test results around the expected results.

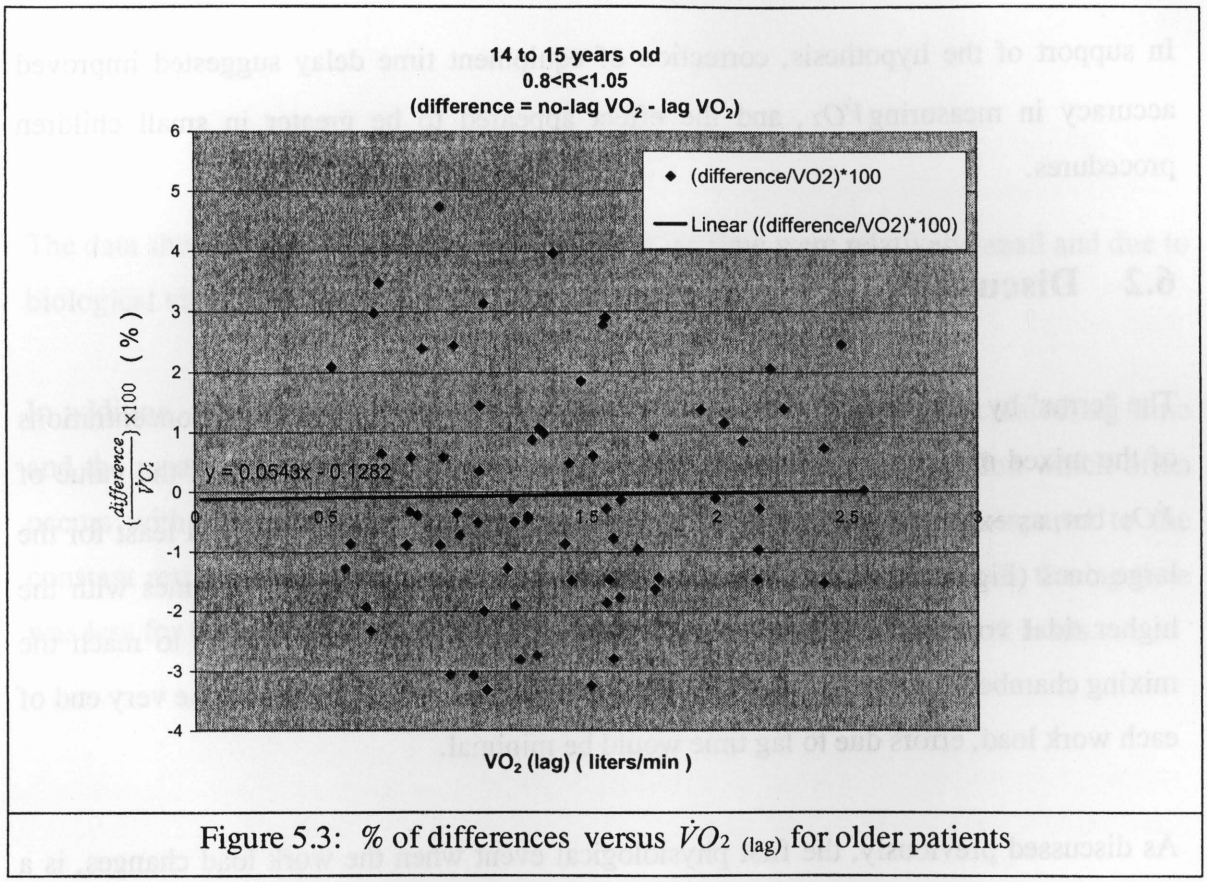


Figure 5.3: % of differences versus $\dot{V}O_{2\ (lag)}$ for older patients

While this relationship did not reach a level of significant ($p > 0.05$), the results suggested that errors were greatest in little children with low $\dot{V}O_2$. This can readily be observed in Figure 5.2 in which a negative slope can be observed for the line depicting that % of difference decreases as the tidal volume of patient increases. On the other hand, bigger children with larger tidal volumes cleared the tubing dead space with a single breath, the lag time was less of an issue and the difference was negligible. See Figure 5.3.

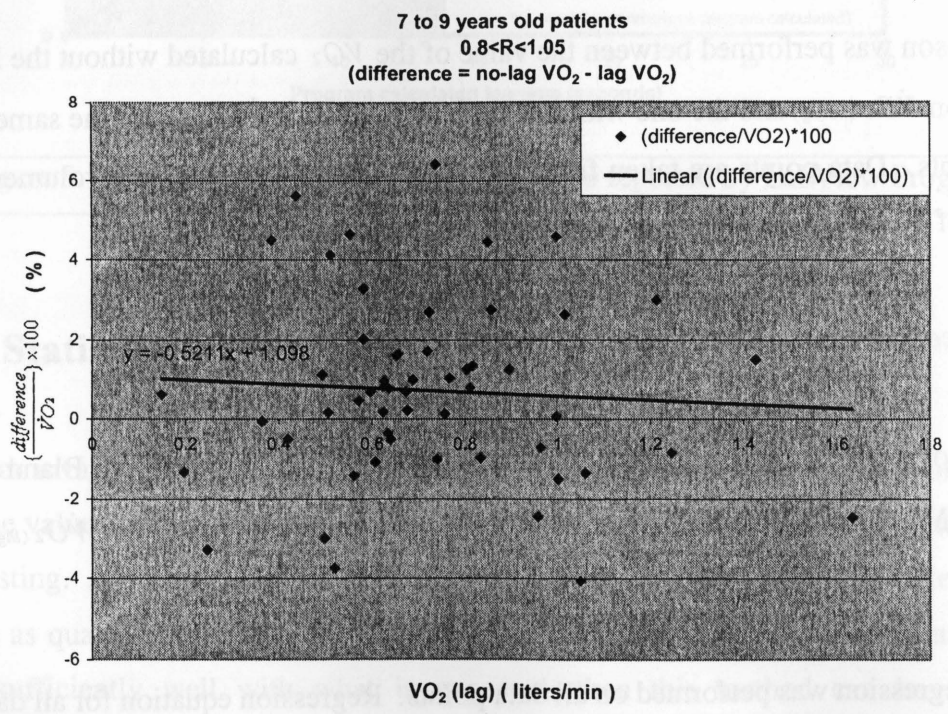


Figure 5.2: % of difference versus $\dot{V}O_{2\,(lag)}$ for smaller patients

Chapter 6

6.1 Conclusion

In support of the hypothesis, correction of equipment time delay suggested improved accuracy in measuring $\dot{V}O_2$, and the effect appeared to be greater in small children procedures.

6.2 Discussion

The "error" by not aligning the inspired ventilation signal to the fractional concentrations of the mixed expired gas were lower than expected, in the range of 1% of the value of $\dot{V}O_2$ but, as expected, were greatest for the small children (Figure 5.2) and least for the large ones (Figure 5.3). This would be in keeping with the shorter lag times with the higher tidal volumes which minimized the time required for expired gas to reach the mixing chamber and the gas analyzers. By looking at the 10-15 seconds at the very end of each work load, errors due to lag time would be minimal.

As discussed previously, the first physiological event when the work load changes, is a rise in expired CO_2 and a fall in O_2. The increase in CO_2 leads to an increase in ventilation and a resulting fall in CO_2. Hence, the benefits of lag time correction would be greatest just after the increase in the work load. This aspect is used for research but for clinical reporting, convention states that the values reported are those at or near the end of the increment of work. Hence it was this époque late in the one minute increment that was chosen for comparison for this project.

The data showed that the errors by not including lag time were relatively small and due to biological variability, did not reach a level of statistical significance.

In addition, there was very reasonable agreement with the program calculated lag time and the measured lag time. Due to a lack of a stable pattern of ventilation which often occurs with children, some discrepancies would be expected when compared to the constant respiratory pattern of the breath simulating ventilator. As expected, the lag time was less for the larger tidal volume seen in the older children at higher work loads.

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