On-line measurement of canine respiratory function and gas exchange using a microcomputer-based system

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LIST OF SYMBOLS

General Symbols	Description	Dimension
$\dot{V}CO_2$	carbon dioxide production	liters/min
$\dot{V}O_2$	oxygen consumption	liters/min
$\dot{V}$	flow	liters/sec
V	volume	liters
F	gas fraction	dimensionless
P	total pressure	mmHg
p	partial pressure	mmHg
LT	lag time	seconds
Δt	time increment	seconds
τ	analyzer time constant	seconds

Modifying Symbols	
A	alveolar
BV	breathing valve (instrumentation) dead space
DS	physiological dead space
E	expired
ET	end-tidal
I	inspired
CO_2	carbon dioxide
H_2O	water
O_2	oxygen

INTRODUCTION

Respiratory function and gas exchange measurements can provide valuable information concerning the condition of the pulmonary and cardiovascular systems as well as whole-body metabolic activity. Consequently, these measurements are used in a wide variety of clinical and research applications.

One of the most common clinical applications of respiratory function and gas exchange measurements is the exercise function test. This test involves measuring respiratory rate, tidal volume, rate of carbon dioxide production ($\dot{V}CO_2$), and rate of oxygen consumption ($\dot{V}O_2$) as an individual exercises at varying work levels. Measurements made during the test are used to evaluate the general fitness of an individual and to aid in the diagnosis and management of diseases of the cardiovascular and pulmonary systems. Other common clinical applications include the use of respiratory function and gas exchange measurements to monitor the condition and recovery of patients during surgery and intensive care.

Measurements of respiratory function and gas exchange are also used in a variety of research applications. For example, they are used to quantify acute and chronic cardiopulmonary changes resulting from exposure to toxic substances and induced pathological conditions. Studies involving animal models can provide information which may lead to the establishment of regulatory and health standards or which may be useful in elucidating the mechanism of a pathological condition or an effective method of therapy. Gas exchange measurements are also frequently used in metabolic and exercise physiology studies. The respiratory quotient, ratio of carbon dioxide produced to oxygen consumed, is an important indicator of whole body metabolic activity. Similarly, maximal oxygen consumption is considered to be an important indicator of athletic performance.

The traditional method for measuring respiratory function and gas exchange requires the use of a mechanical gas meter for measuring air flow, Douglas-type bags for collecting expired gas samples, and chemical gas analyzers for determining the gas fractions in the expired air samples. Three major disadvantages of the traditional method are: 1) a considerable amount of time and energy are required for sampling and collection of data, analysis of expired gas samples, and computation of the final results, 2) expired air samples are usually collected over several minutes; therefore, measurements are an average of a relative large number of breaths, and 3) the final results are usually not known until after the test or experiment when the analysis of gas samples and the calculation of derived values can be completed.

In contrast, the development of electronic flowmeters and rapidly responding gas analyzers has made the continuous measurement of inspired and expired flow and gas concentrations possible. Likewise, computers have substantially reduced the amount of time required for data collection and computation. Together these developments have made on-line measurement of respiratory function and gas exchange practical.

There have been two distinct approaches to the development of computer-based systems for on-line measurement of respiratory function and gas exchange. The first approach is very similar to the traditional method of gas exchange measurement. However, rather than being collected in a Douglas-type bag the expired air is passed through a mixing chamber from which the gas analyzers sample mixed-expired air. The product of minute ventilation and the difference between inspired and expired gas concentrations gives the rate of gas exchange as measured at the mouth. The advantage of this first approach is the relatively simple computation involved. A disadvantage is that like the traditional method this approach yields gas exchange values which are averages of a large number of breaths.

The second approach is to measure inspired and expired air flow and gas concentrations continuously. By integrating the product of the flow and gas concentration signals over time, gas exchange can be computed on a breath-by-breath basis. An advantage of this second approach is that transient changes in respiratory function or gas exchange can be detected and observed. Another advantage is that this method can be adapted to other techniques requiring breath-by-breath analysis of respiratory gas exchange, such as single breath cardiac output determination. Disadavantages include a more complicated computation algorithm which is particularly dependent on aligning the flow and gas concentration signals with respect to time.

Although most clinical systems developed for measuring respiratory function and gas exchange are now computer-based, the traditional method of measurement is still frequently used in research applications involving animals. There are several reasons for the limited application of computer-based measurement systems to animal research. First, computer-based systems tend to be relatively complex and expensive. Second, most computer-based systems have been designed for human clinical applications, and therefore, may require modifications for use with research animals or in a research setting where flexibility is important.

The purpose of this project is to implement a flexible, low-cost, microcomputer-based system for on-line breath-by-breath analysis of respiratory function and respiratory gas exchange. The system is to be directed toward research and possibly clinical applications involving dogs or other animals in the range of 15 to 75 kg.

LITERATURE REVIEW

The Breath-by-Breath Method

Although the specific types of flowmeters, gas analyzers, and computers may vary from one measurement system to another, the basic computation algorithms used to compute inspired volume, expired volume, rate of carbon dioxide production, and rate of oxygen consumption are usually quite similar. The following equations are of the form commonly used to compute respiratory function and gas exchange variables on a breath-by-breath basis.

$$V_I = \int_{insp} \dot{V}_I \, dt \tag{1}$$

$$V_E = \int_{exp} \dot{V}_E \, dt \tag{2}$$

$$VCO_2 = \int_{exp} \dot{V}_E FCO_2 \, dt - \int_{insp} \dot{V}_I FCO_2 \, dt \tag{3}$$

$$VO_2 = \int_{insp} \dot{V}_I FO_2 \, dt - \int_{exp} \dot{V}_E FO_2 \, dt \tag{4}$$

For digital computer applications, the integrals in the above equations can be approximated by numerical methods of integration such as the rectangle rule, the trapezoid rule, or the more complex Simpson's parabolic rule of integration.

Instrumentation

Some of the earliest systems for breath-by-breath analysis of respiratory function and gas exchange include those described by Auchincloss et al. (1968), Lipsky and Angelone (1967), and Murphy (1966). These early systems employed analog computers for either part or all of the computation. Pneumotachographs and fast responding gas analyzers, such as infrared carbon dioxide and paramagnetic oxygen analyzers, were used to measure air flow and gas concentrations, respectively.

Because they tend to be more flexible than their analog counterparts, most of the recently described systems have been developed using digital computers (Sodal et al., 1983; Salminen et al., 1982; Miyamoto et al., 1981; Sue et al., 1980; Pearce et al., 1977; Beaver et al., 1973). Although many computer-based systems have been developed using fast responding gas analyzers (Salminen et al., 1982; Sue et al., 1980; Pearce et al., 1977; Beaver et al., 1973), an increasing number of systems have been developed using single respiratory mass spectrometers capable of measuring several gases (Gronlund, 1984; Sodal et al., 1983; Giezendanner et al., 1983; Miyamoto et al., 1981; Beaver et al., 1981). There have also been a number of systems developed using either impedance plethysmography (Miyamoto et al., 1981) or hot-wire anemometers (Gronlund, 1984; Shimada et al., 1984; Sodal et al., 1983) rather than pneumotachographs to measure air flow.

Though the various combinations of instruments offer particular advantages and disadvantages all of these computer-based systems require the same basic input signals, respired air flow and gas concentrations.

Computation Algorithms

Several investigators in attempts to simplify the computation and reduce the amount of instrumentation required for breath-by-breath analysis have used modified versions of equations 3 and 4 (Salminen et al., 1982; Miyamoto et al., 1981; Sue et al., 1980; Pearce et al., 1977; Beaver et al., 1973). Simplification of the gas exchange equations is based on two conditions or assumptions. First, the equation for computing carbon dioxide production can be simplified when room air, which contains a negligible amount of carbon dioxide, is being inspired. Second, the equation for computing oxygen consumption can be simplified by assuming that the amount of nitrogen expired is equal to the amount inspired. If nitrogen balance is a valid assumption, the volume of wet inspired air can be computed from the wet expired volume using the following equation.

$$V_I = V_E + V_I H_2O - V_E H_2O + V_I CO_2 - V_E CO_2 + V_I O_2 - V_E O_2 \tag{5}$$

Using these two simplifications equations 3 and 4 can be rewritten in the following form.

$$VCO_2 = \int_{exp} \dot{V}_E FCO_2 \, dt \tag{3'}$$

$$VO_2 = V_I F_I O_2 - \int_{exp} \dot{V}_E FO_2 \, dt \tag{4'}$$

The condition of negligible inspired carbon dioxide and assumption of nitrogen balance allow gas exchange to be computed from only the expiratory phase of the respiratory cycle. Thus, the complexity of the computation and required instrumentation is substantially reduced.

Although the assumption of nitrogen balance has been incorporated into the design of many computer-based systems, this assumption is not always valid (Wessel et al., 1979), particularly during nonsteady-state conditions such as the onset of exercise. To account for changes in functional residual capacity (FRC) and changes in alveolar gas concentrations, both inspired and expired flow as well as the concentrations of inspired and expired oxygen, carbon dioxide, and nitrogen should be measured continuously at the mouth.

Some computer-based systems have been designed to take into account breath-by-breath changes in lung gas storage using relatively complicated computation algorithms (Gronlund, 1984; Giezendanner et al., 1983; Beaver et al., 1981; Auchincloss et al., 1968). There is, however, a simpler alternative. By averaging an increasing number of breath-by-breath measurements, which are made using only the expiratory phase of respiration, the mean gas exchange as measured at the mouth should approach the mean gas exchange across the lung alveoli. In other words, over an increasing number of respiratory cycles the total amount of nitrogen expired should equal the amount inspired and consequently the assumption of nitrogen balance should be valid.

Corrections and Compensations

There are number of corrections and compensations which are commonly applied to respiratory function and gas exchange measurements, such as corrections for differences in the water vapor content and the temperature of inspired and expired air (Brunner et al., 1983; Beaver, 1973), and compensation for the lag time and response of the gas analyzers (Bernard, 1977; Mitchell, 1979). Failure to make the necessary corrections and compensations can lead to significant errors in the computed respiratory function and gas exchange values.

With respect to corrections and compensations, one of the major areas of investigation has been the compensation for the lag time and response of gas analyzers. Because the product of the flow and gas concentration signals is numerically integrated to obtain breath-by-breath measurements of gas exchange, these signals must be aligned with respect to time. Using a simulated model, Bernard (1977) determined that to be within 5% of the actual gas exchange value the flow rate and gas concentration signals should not be out of phase by more than 25 ms.

However, there is a substantial delay or lag time between the moment flow is sensed and the time the gas sample travels through the sample line and reaches the analyzer. In addition to the transport delay or lag time, the analyzer's output signal is also distorted by the dynamic response of the analyzer. Several methods of compensation have been described. The simplest method is to realign the flow and gas concentration signals based on a delay which is the sum of the lag time and the time constant of the analyzer's response to a step change in gas concentration (Beaver et al., 1973).

Mitchell (1979) and later Noguchi et al. (1982) described a more complicated method of compensation which is based on the approximation of the dynamic response of an analyzer by a first-order differential equation of the form

$$Y(t) = y(t+LT) + \tau y'(t+LT) \tag{6}$$

where Y is the recovered "input signal" to the analyzer and y, LT, and τ are the analyzer output, lag time, and time constant, respectively.

Mitchell (1979) found that not accounting for the dynamic response of the analyzer, both fast responding gas analyzers and mass spectrometers, resulted in a 20% underestimation of gas exchange. Nevertheless, the first-order compensation for the response of a mass spectrometer as described by Noguchi et al. (1982) has several problems which include overshoot, sensitivity to signal noise, and sensitivity to small changes in the estimated analyzer time constant. Mitchell (1979), however, does indicate that by placing the differential equation within the integral of the flow gas concentration product of equations 3 and 4, both the sensitivity to noise and sensitivity to small changes in the analyzer time constant can be reduced.

Arieli and Van Liew (1981) found that a second-order differential equation of the following form better represents the sigmoid shape of the analyzer (mass spectrometer) response curve.

$$Y(t) = y(t+LT) + (\tau_1+\tau_2)y'(t+LT) + \tau_1\tau_2 y''(t+LT) \tag{7}$$

Once again Y is the recovered "input signal" to the analyzer and y, LT,

τ_1, and τ_2 are the output signal, lag time, and time constants, respectively. The two-exponent model also has several problems which include the empirical method by which the time constants are estimated and the substantial amount of computation necessary to recover the corrected signal. The first time constant is purposely underestimated in order to reduce overshoot in the recovered "input signal." The second time constant is obtained from the once corrected response of the analyzer.

More recently Bates et al. (1983) compared three methods of compensation for the dynamic response of a respiratory gas analyzer (mass spectrometer). The three methods compared were: 1) the simple time delay compensation, 2) the second-order compensation described by Arieli and Van Liew (1981), and 3) a Fourier transform method of deconvolution known as Weiner filtering. Although Weiner filtering was found to be the most accurate method of compensation, all three methods provided a substantial reduction in measurement error. However, because of the complex computation involved, Weiner filtering is probably not practical for on-line applications.

Tavener et al. (1984) in their attempt to model the response of a respiratory gas analyzer (mass spectrometer) found that estimates of transport delays (lag times) and time constants were dependent on the gas composition and the direction of the applied step change. Thus, they concluded that "complex correction procedures are unlikely to yield useful benefits." Instead, they proposed that more emphasis be placed on the accurate determination of the transport delay and a single time constant rather than a more complicated second-order compensation procedure.

Although not directly related to correction and compensation, factors such as sampling frequency and signal preprocessing can also have a significant effect on computed values. Using simulated signals Bernard (1977) found that "a trapezoidal rule integration at a sample rate of 30 Hz with no numerical filtering can provide satisfactory results." Nevertheless, most systems use sampling frequencies of approximately 50 Hz with some type of analog or numerical (digital) filtering of the input signals. Systems have been described that use sampling frequencies from as low as 25 Hz (Salminen et al., 1982) to well over 100 Hz (Wessel et al., 1979).

As stated earlier, most systems for on-line breath-by-breath analysis of respiratory function and gas exchange have been developed for human clinical and research applications. However, as a part of their validation procedure Shimada et al. (1984) tested their system on mechanically ventilated rabbits and dogs. Their computer derived values for gas exchange correlated well with simultaneous mixed expired measurements and included gas exchange rates from approximately 10 to 70 ml/min. In a study of the kinetics of exercise, Casaburi et al. (1979) mention the use of a computer-based system described by Beaver et al. (1973) for on-line measurement of gas exchange. Measurements were made on anesthetized dogs that were mechanically ventilated.

DEVELOPMENT

Apparatus

The measurement system is centered around a Commodore-128 personal computer. The Commodore-128 contains 128 kilobytes of user memory, expandable to 512 kilobytes, and has a built in BASIC interpreter and machine language monitor. The computer has two eight-bit microprocessors, an 8502 which is used for BASIC and machine language programs and a Z80A for CP/M programs. The 8502 microprocessor, which was used in this project, can be run either at 1 or 2 MHz. However, the 2 MHz mode is limited to programs or portions of programs that do not contain graphics. Peripheral devices used in conjunction with the computer include a 360 kilobyte 5.25 inch disk drive, a 40/80 column color monitor, and a dot-matrix printer.

A Beckman LB-2 infrared-type fast responding medical gas analyzer was used for continuous measurement of the concentration of carbon dioxide in respired air. At a sample flow rate of 500 ml/min, the typical response time for the analyzer is given as 100 ms for a 90% response to a step change in carbon dioxide concentration. The Beckman LB-2 has a linear operating range of 0 to 10% carbon dioxide. The analyzer has accessory outputs which provide filtered, linearized, and amplified signals of 0 to 100 mV and 0 to 5 V dc.

A Beckman OM-11 polarographic-type fast responding medical gas analyzer was used for continuous measurement of the concentration of oxygen in respired air. At a sample flow rate of 500 ml/min, the typical response time for the analyzer is given as 100 to 150 ms for a

90% response to a step change in oxygen concentration. The Beckman OM-11 has a linear operating range of 0 to 100% oxygen. The analyzer has accessory outputs which provide filtered, linearized, and amplified signals of 0 to 100 mV and 0 to 5 V dc for two ranges, 0 to 25% and 0 to 100% oxygen. The Beckman OM-11 also contains electronic circuitry which partially compensates for the analyzer's exponential response to a step change in oxygen. Both the Beckman LB-2 and OM-11 have digital displays. Although both instruments are actually partial pressure sensing devices, measured values are displayed as concentrations.

A heated Fleisch model 1 pneumotachograph is used in conjunction with a Statham PM5 differential pressure transducer to measure air flow. The linear range of the pneumotachograph is given as 0 to 60 l/min.

The breathing apparatus, through which respired air passes, is configured such that an intubated animal can be connected directly to the pneumotachograph. The opposite end of the pneumotachograph is connected to a low dead space (18 ml) model 1400 Rudolph two-way nonrebreathing valve. The combined dead space of the pneumotachograph and breathing valve is approximately 40 ml. Respired air was sampled at the connection between the pneumotachograph and the breathing valve at a rate of approximately 350 ml/min through a 77 cm long heated sampling tube. Because the gas analyzers were connected in series only one sample line was required.

The analog signals from the two gas analyzers and the differential pressure transducer were sent directly to an eight channel Beckman type R411 Dynograph recorder for display. The recorder also provides some signal conditioning, amplification and low-pass filtering. The conditioned analog output signals from the recorder are limited to ± 1.414 V dc. These are the signals sent to the computer to be sampled and digitized.

In order to make the sampling of analog signals possible an input/output board was added to the Commodore-128 (MW-611, Micro World Electronix, Lakewood, CO). The input/output board contains an eight-bit analog-to-digital converter with a conversion time of 100 μsec (NSC ADC0817). The analog-to-digital converter has a built in multiplexer allowing up to 16 input channels. To be compatible with the input/ouput board's analog-to-digital converter, the analog signals from the recorder were offset and amplified to a range of 0 to 5 V dc.

A block diagram of the measurement system appears in Figure 1.

Practical Considerations

One of the most important considerations is the quality and condition of the input signals. All three instruments, the two gas analyzers and pneumotachograph/differential pressure transducer, produce signals which are linear over their specified measurement ranges. These instruments provide electronically filtered output signals which are relatively noise free. The pneumotachograph/differential pressure transducer unit is quite stable and can go several weeks before requiring recalibration. In contrast, the gas analyzers require recalibration before each experiment and are subject to drift if they are not warmed-up for at least several hours as recommended in their instruction manuals.

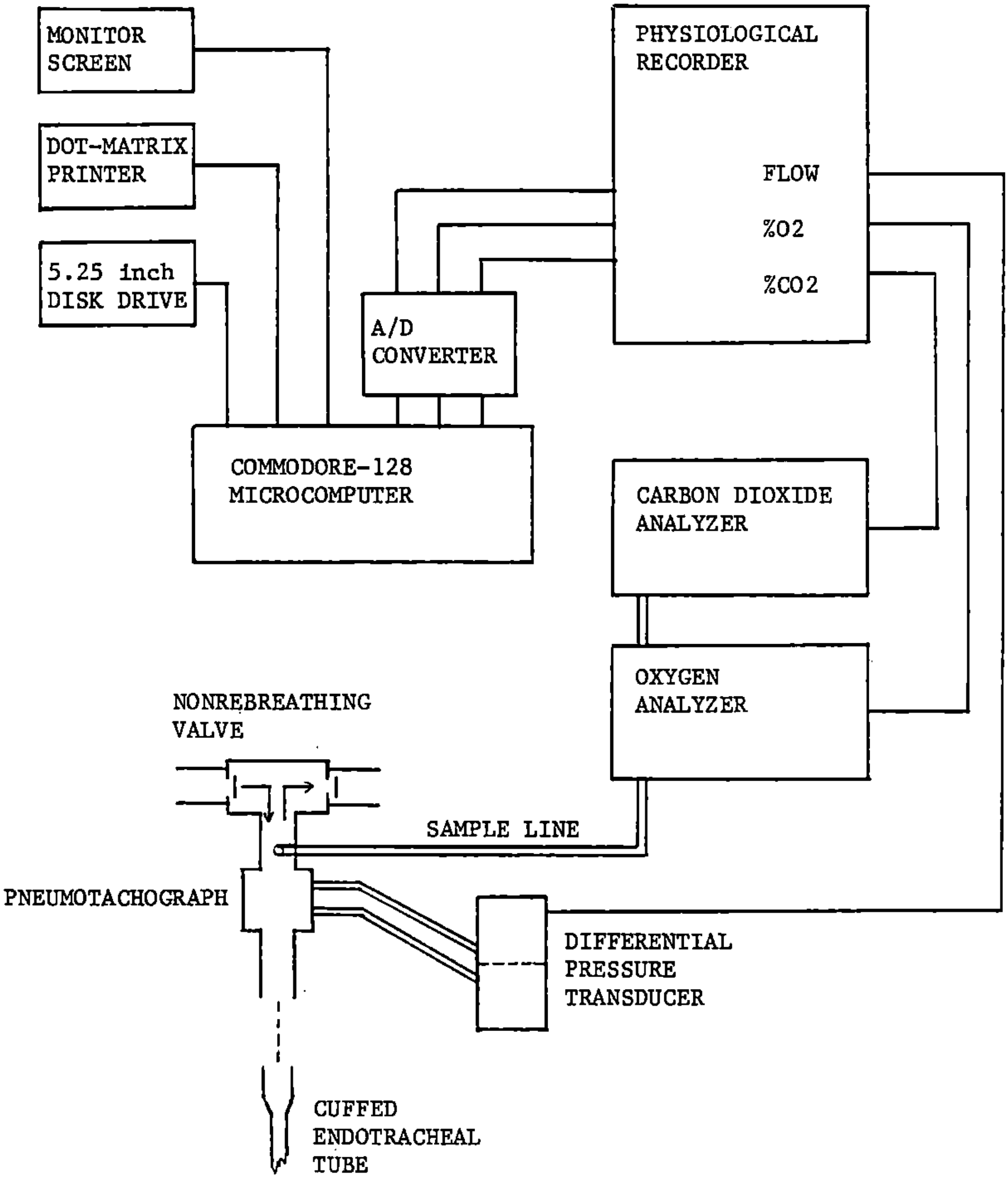


Figure 1. Block diagram of measurement system

Although the gas sample line is heated, water in the expired air condenses in the sample line and the analyzer pick-up heads. During the course of a long experiment, the build up of condensation in the pick-up heads tends to degrade the analyzers' performance. To avoid condensation problems, the sampled air can be passed through a drying tube. However, this procedure also tends to degrade the analyzers' performance. An effective alternative is to sample room air rather than respired air while measurements are not being made.

Another important consideration is the process by which the analog signals are sampled and digitized. One of the advantages of using a physiological recorder is that preprocessing of the input signals to the computer is possible. The flow and gas concentration signals can be amplified by adjusting the sensitivity settings of the recorder. Use of the entire output range of the recorder, ± 1.414 volts, is particularly important with respect to the resolution of the analog-to-digital conversion process.

The analog-to-digital converter used in this project is an eight-bit converter. Thus, for an analog input range of 0 to 5 V dc there is a corresponding range of digital values from 0 to 255. And although the maximum resolution of the conversion process is 1/256 or 0.4% the effective resolution may be much lower if only a fraction of the available input range is used. Therefore, to reduce errors associated with the digitization process the amplitude of the signal should approach the input limits of the analog-to-digital converter.

Because digital computation is a discrete process, analog signals or other continuous processes can only be approximated. Valid reconstruction of continuous functions, such as the gas concentration and flow signals, is dependent not only on the resolution of the conversion process but also on the frequency of the sampled signals and the frequency or rate at which they are sampled.

Although Bernard (1977) found that a sampling frequency of 30 Hz provided adequate information for accurate computation of gas exchange in humans, a sampling frequency of approximately 65 Hz was chosen for this project. The faster sampling frequency provides for a wide range of respiratory rates which maybe encountered in animals of varying sizes. Furthermore, the faster sampling frequency provides compatibility with the low-pass filtering available on the Beckman type R411 recorder.

The sampling theorem requires that the sampling frequencey should be at least twice the highest frequency component of the analog signal if the original signal is to be recovered without any distortion. The most convenient high frequency cutoff setting available on the recorder is 30 Hz. And although Salminen et al. (1982) determined that the essential components of the flow and gas concentration signals were below 8 Hz (data were obtained from humans), to be consistent with the sampling theorem and the 30 Hz cutoff of the recorder, a sampling frequency of at least 60 hz is required.

Other considerations related to the use of a microcomputer for on-line applications include memory capacity and speed of computation. With 128 kilobytes, which can be expanded to 512 kilobytes, the Commodore-128 can accommodate a relatively large program and still have plenty of memory available for temporary data storage. Data can also be stored in a more permanent form on 5.25 inch floppy disks. Storing large amounts of data to disk can take several minutes, and therefore, is usually not practical. However, sampled data were stored to disk as a means of testing changes in the program. The stored data could be loaded from the disk and processed back through the program as needed.

With respect to speed of computation, an assembly language program will run significantly faster than a program written in a high-level language such as BASIC. However, assembly language programs tend to be less flexible and more difficult to write and edit. Therefore, the program, except for an assembly language sampling subroutine, was written entirely in BASIC. The use of an assembly language sampling subroutine allows data to be collected at frequencies far greater than would be possible using BASIC commands. As an example, the maximum rate at which three channels can be sampled using BASIC commands is approximately 60 Hz. If assembly language commands are used, the maximum rate at which three channels can be sampled is over 1000 Hz.

The relatively slow execution of BASIC commands does substantially limit the amount and complexity of on-line computation. As a result, complex computations, such as those described by Noguchi et al. (1982) and Arieli and Van Liew (1981) for the compensation of the lag time and response of an analyzer, may not be practical. For instance, the method described by Noguchi et al. (1982), which requires digital filtering of the sampled data and numerical differentiation, increases the computation time several fold. The time required for computing respiratory function and gas exchange variables from data collected over a 10 to 20 second sampling period is increased from approximately 30 seconds to almost 2 minutes.

Finally, consideration should be given to the configuration of the breathing apparatus. The configuration used in this project was based on an early attempt to measure both the inspiratory and expiratory flows using a single pneumotachograph connected directly to the tracheal tube of an intubated animal and on the requirements of other investigators who were using the equipment. However, if only the expiratory flow is to be used in the computation of respiratory function and gas exchange variables, the pneumotachograph can be connected to the expiratory arm of the breathing valve.

Moving the pneumotachograph to the expiratory arm of the breathing valve would substantially reduce the instrumentation dead space volume. For animals with relatively small tidal volumes rebreathing of instrumentation dead space air can be a significant problem. As the dead space to tidal volume ratio is increased, the animal's effective ventilation decreases. Furthermore, larger and larger corrections of the computed gas exchange values may be required. Finally, by moving the pneumotachograph away from the mouth or endotracheal tube, errors in the flow measurements due to turbulence and sudden changes in air temperature and viscosity which occur during the respiratory cycle will be reduced (Brunner et al., 1983).

Computation Algorithms

As stated earlier, an initial attempt was made to measure air flow during both the inspiratory and expiratory phases of the respiratory cycle using a single pneumotachograph connected directly to the endotracheal tube of an intubated animal. However, this approach proved to be fairly complex and the derived gas exchange values were particularly sensitive to small errors in the computed inspired and expired volumes.

A second and more successful approach was taken which involved measuring only the expiratory phase of the respiratory cycle. Satisfactory results were obtained using the simplified gas exchange algorithms of equations 3' and 4'. The conditions for using the simplified algorithms can be satisfied if either room air or a gas mixture which does not contain carbon dioxide is being inspired and gas exchange values are computed as the mean of a group of breaths, usually four or more breaths.

Below is a list of assumptions, definitions, and identities which were used to rewrite equation 2, 3', and 4' in forms consistent with the input signals and environmental conditions.

1. The oxygen and carbon dioxide analyzers are partial pressure sensing devices, and therefore, are sensitive to changes in the water vapor content of sampled air. To determine dry gas fractions a correction for water vapor content should be made as follows.

$$F_{dry} = F_{wet} \frac{P}{(P-pH_2O)} \qquad (8)$$

2. The pneumotachograph is calibrated using room air. Therefore, flow values correspond to air at ambient temperature and pressure. However, corrections for the different water contents of inspired and expired air are required.

3. Inspired air at ambient temperature is assumed to be 60% saturated. Expired air is assumed to be 5 °C below body temperature and 95% saturated (Brunner et al., 1983). The following equation is used to estimate the partial pressure of water in 100% saturated air for a given temperature, T, in degrees Kelvin (Brunner et al., 1983).

$$pH_2O \text{ (mmHg)} = 3160.89 - 22.45 * T + 0.04 * T^2 \qquad (9)$$

4. The definite integrals in equations 2, 3' and 4' are approximated using the rectangle rule of integration. The summation sign, $\sum_{i=1}^{N}$, is used to indicate numerical integration, where N is the number of digital samples taken during the expiratory phase of the respiratory cycle, N = (sampling frequency)*(expiratory period).

5. The inspired volume is computed from the expired volume using equation 5 which is repeated here in a simplified form.

$$V_{I_{dry}} = V_{E_{dry}} - VCO_2 + VO_2 \qquad (5')$$

VCO_2 and VO_2 are the measured volumes of carbon dioxide produced and oxygen consumed during the respiratory cycle, respectively.

Rewriting equations 2, 3', and 4' using the above listed assumptions, definitions, and identities gives:

$$V_E = k1 \sum_{i=1}^{N} \dot{V}_E \, \Delta t \tag{2}$$

$$VCO_2 = k2 \sum_{i=1}^{N} \dot{V}_E FCO_2 \, \Delta t \tag{3'}$$

$$VO_2 = \frac{(k2 \, V_E - VCO_2)F_IO_2 - k2 \sum_{i=1}^{N} \dot{V}_E FO_2 \, \Delta t}{1 - F_IO_2}, \tag{4'}$$

where $k1 = \frac{P - pH_2O}{P}$, $k2 = \frac{(P)(273)}{(760)(T_a)}$, F_IO_2 is the dry gas fraction of inspired oxygen, and Δt is the time between successive samples (Δt = 1/sampling frequency). The constants k1 and k2 are used to correct the expired volume to ATPD and the gas exchange values to STPD, respectively. T_a is the ambient temperature.

Two additional corrections or compensations were applied to the gas exchange equations, one for rebreathing of instrumentation dead space and the other for the lag time and response of the analyzers. The correction for rebreathing of instrumentation dead space can be carried out as follows.

$$VCO_2 = k2 \sum_{i=1}^{N} \dot{V}_E FCO_2 \, \Delta t - V_{BV} F_{ET}CO_{2_{dry}} \tag{3''}$$

$$VO_2 = \frac{(k2 \, V_E - VCO_2 - V_{BV})F_IO_2 + V_{BV}F_{ET}O_{2_{dry}} - k2 \sum_{i=1}^{N} \dot{V}_E FO_2 \, \Delta t}{1 - F_IO_2} \tag{4''}$$

V_{BV} is the breathing valve or instrumentation dead space volume. The computed gas exchange values are corrected for that fraction of inspired air which is not fresh inspired air but is in fact expired air being rebreathed. Although not shown in equations 3'' and 4'', the instrumentation dead space volume is corrected to STPD. The air being rebreathed from the dead space is expired air and therefore is assumed to be 5 ^{o}C below body temperature and 95% saturated.

The second compensation is for the lag time and response of the analyzers. Although a number of different methods of compensation have been proposed, due to computation time restraints only what appeared to be the three most practical methods were tested. For all three methods the lag time, LT, was estimated as the time between the introduction of an input step change to the analyzer and the beginning of the output response. Likewise, the time constant, τ, of the analyzer was estimated as the time between the beginning of the analyzer's output response to a step change in gas concentration and the time at which the output reaches 63% of full response.

The first method is a simple time delay compensation. The analyzer signals are in effect shifted back in time by the sum of the measured lag time and the time constant of the analyzer's response to a step change in gas concentration. The second and third methods are based on a first-order compensation for the lag time and response of the analyzers. The first-order compensation was given in equation 6 and is repeated below.

$$Y(t) = y(t+LT) + \tau y'(t+LT) \qquad (6)$$

Once again, LT is the lag time and τ is the time constant of the analyzer. The derivative in equation 6 is commonly approximated by a two point difference equation of the form $y'(t) = (y(t+\Delta t) - y(t))/\Delta t$, where Δt is the time between successive samples.

What distinguishes methods two and three is how the first-order compensation is applied. As described by Noguchi et al. (1982) the compensation is carried out prior to integration of the flow gas concentration product. In contrast, Mitchell (1979) placed the compensation equation within the integral of the flow gas concentration product in an attempt to reduce the amount of computation required and reduce the sensitivity of the compensation to noise and small errors in the estimated time constant. Before rearranging, the equation used by Mitchell for computing the inspired or expired volume of gas j is of the form

$$V_j = \sum_{i=1}^{N} \dot{V}\left(\frac{\tau}{\Delta t}(y_{j,i+1} - y_{j,i}) + y_{ij}\right) \Delta t \tag{10}$$

where Δt is the time between successive samples, τ is the time constant of the analyzer, $\dot{V}$ is air flow, and y is the lag time corrected gas concentration.

After applying the necessary corrections and compensations respiratory rate, tidal volume, minute ventilation, rate of carbon dioxide production, and rate of oxygen consumption can be computed from a group of breaths which occurred during a known sample period. End tidal or end expired carbon dioxide and oxygen gas concentrations are taken to be, respectively, the maximum and minimum concentrations measured during the expiratory phase of each breath. Finally, physiological dead space volume can be computed on a breath-by-breath basis using the Bohr equation (Comroe et al., 1962) and assuming that the end-expired concentration of carbon dioxide is either equal to or very close to the alveolar concentration

$$V_{DS} = V_E - \frac{VCO_2}{F_A CO_2} = V_E - \frac{VCO_2}{F_{ET} CO_2} \qquad (11)$$

V_E and VCO_2 are the volumes of air expired and carbon dioxide produced during a single respiratory cycle, respectively. Like the other respiratory variables, the final physiological dead space volume is computed as the average value obtained from a group of breaths.

Program Description

The program was developed with several goals in mind. First, the program should be flexible enough to meet the needs of different users. Second, the program should be easy to use, and if necessary edit. To meet these goals the program was written in BASIC as a series of subsections or subroutines. The program is menu driven which makes the program easy to use yet provides enough freedom for the user to control program flow. A summary of the operating instructions appears in Appendix A. The main program along with the assembly language sampling program is listed in Appendix B.

The main program is composed of four major subroutines. They are: 1) a data entry subroutine, 2) a calibration subroutine, 3) a data collection and computation subroutine, and 4) a graphics subroutine. Each subroutine has either direct access to the others or indirect access through the primary menu. A simplified block diagram of the program appears in Figure 2.

The data entry subroutine is used to enter or change variables related to program control and environmental conditions. These variables are saved on the disk in two separate files. Upon starting the program, the user is prompted for information such as the sampling frequency, the number of samples that are to be collected, and the ambient temperature and pressure. A selection for the data entry subroutine (control and environmental variables) appears on the primary menu. Thus, the user can return to the subroutine as required.

The calibration subroutine provides a step-by-step procedure for calibrating the gas analyzers and measuring the lag times and time constants of the carbon dioxide and oxygen analyzers. A two-point calibration of the analyzers is performed using room air and a calibration gas composed of approximately 5% carbon dioxide, 15% oxygen, and 70% nitrogen. A linear conversion equation is computed for each analyzer and is used during computation to convert the sampled digital values (0-255) to corresponding gas fractions.

The lag times and time constants for both analyzers are measured using the method descirbed by Noguchi et al. (1982). Briefly, a balloon is placed inside of a 2 liter plastic container which is connected to the pneumotachograph and inflated with the calibration gas, 5% carbon dioxide and 15% oxygen. The balloon is then popped creating an almost instantaneous change in the flow and gas concentrations, input step changes. The outputs from the pneumotachograph and two gas analyzers are sampled and digitized at approximately 250 Hz during this procedure.

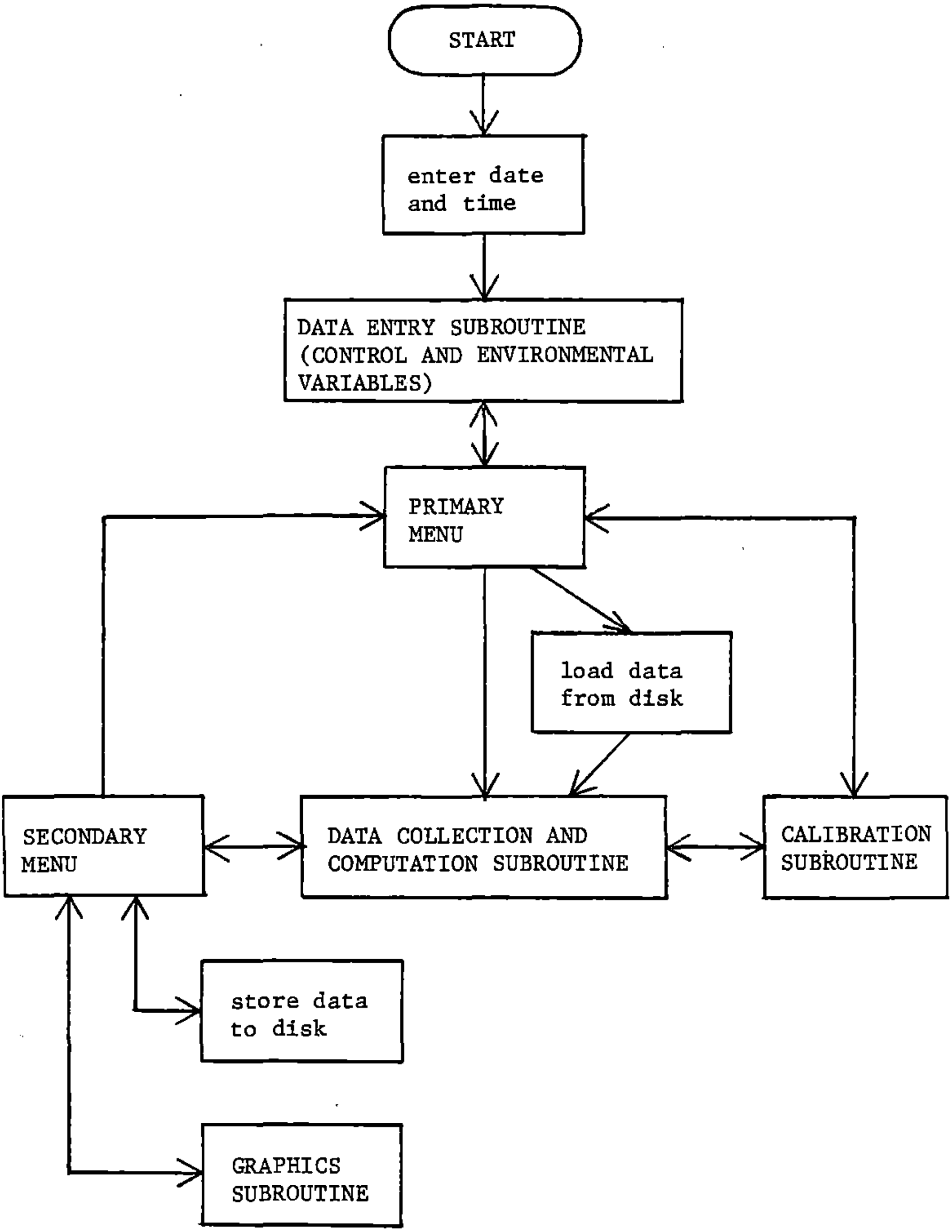


Figure 2. Block diagram of program (arrows indicate the directions in which program flow can occur)

The analyzer lag times are computed as the time between the pneumotachographs response to the step change, which is for practical purposes instantaneous, and the point at which the analyzers begin to respond. The time constant of the analyzers response is measured as the time between the beginning of the analyzer's output response and the point at which the output reaches 63% of full response. Typical lag times for the carbon dioxide and oxygen analyzers are 0.345 and 0.330 seconds, respectively. Typical time constants for the carbon dioxide and oxygen analyzers are 0.120 and 0.090 seconds, respectively.

Because accurate determination of lag times and time constants is so important, this part of the calibration subroutine is repeated 3 to 4 times and average lag times and time constants are computed. Both the analyzer lag times and time constants can be reduced by decreasing the length of the sampling tube or increasing the rate at which air is sampled by the analyzers.

For the most part, the pneumotachograph is calibrated off-line. Calibration is done <u>in situ</u> using ambient air at approximately ten different flow rates varying from 0 to 60 liters/min. Flow is measured with a mechanical gas flowmeter (Singer, American Meter Division). A least-squares linear regression is performed using the measured flow rates and corresponding digital values to obtain the best-fit linear equation. The slope and intercept from the regression equation are entered into the program as control variables and are used in a conversion equation similar to those used for the gas analyzers. Although, more intricate methods of calibration and modeling of the pneumotachograph's output have been described (Yeh et al., 1982; Wessel et al., 1979) a simple linear equation proved adequate for the range of flows being measured, 0 to 75 l/min.

The calibration subroutine of the program is used to find the flow zero, the digital value corresponding to zero flow, and perform a volume check. The volume check consists of injecting a known volume of air, usually 1 liter, from a 2 liter calibrated syringe through the pneumotachograph. The computed volume can then be compared with the known volume to determine if the pneumotachograph requires recalibration. Like the control and environmental variables the calibration constants are saved on the disk in a separate file.

The data collection and computation subroutine begins with the collection of data during a user defined sample period, commonly 10 to 20 seconds. The assembly language sampling program is initialized by the BASIC program just prior to the collection of data. Control vairables such as the number of samples and the delays necessary to sample at the specified frequency are sent from the BASIC program to the assembly language program using POKE commands. The sampled data are stored directly into the arrays from which the BASIC program obtains the data for computation of respiratory function and gas exchange variables.

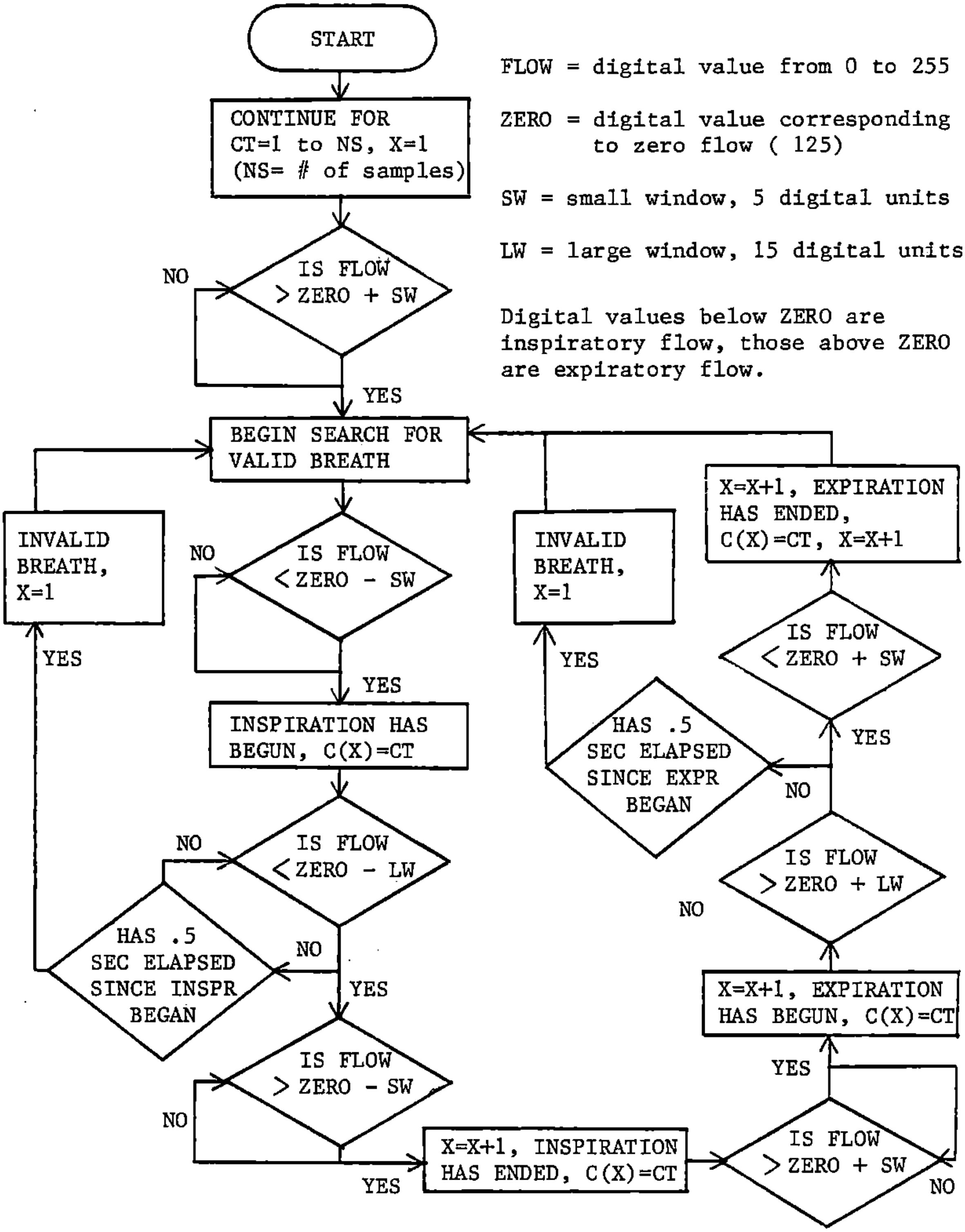
After the data have been collected, the flow signal is analyzed and the beginning and end of both inspiration and expiration are identified for each breath that occurred during the sample period. However, because only the expiratory phase of respiration is used in the simplified computation of respiratory fuction and gas exchange, identifictaion of the beginning and end of inspiration is not required and could be removed from the program. A flow diagram of the breath analysis section of the program appears in Figure 3.

Tidal volume, carbon dioxide production, oxygen consumption, physiological dead space, and end-tidal gas concentrations are computed on a breath-by-breath basis using only the expiratory phase of each respiratory cycle. Average tidal volume, carbon dioxide production, and oxygen consumption values from the sample period are multiplied by the computed respiratory rate to obtain minute ventilation and gas exchange rates.

Tidal volume, minute ventilation, and physiological dead space values are corrected to ATPD. Oxygen consumption and carbon dioxide production values are corrected to STPD. The end-tidal concentrations are converted to partial pressures and expressed in mmHg. An example print-out of the control and environmental variables, the calibration constants, and the computed respiratory function and gas exchange values appears in Figure 4.

The respiratory function and gas exchange values that appear in Figure 4 were computed from data that had been previously stored on the disk. Respiratory function and gas exchange values were computed using the three different methods of compensation for the lag time and response of the analyzers; the simple time delay compensation, the first-order compensation described by Mitchell (1979), and the first-order compensation described by Noguchi et al. (1982).

Using the simple time delay compensation, new respiratory function and gas exchange values can be computed and printed out at approximately one to two minute intervals. The computation time is dependent on the



FLOW = digital value from 0 to 255

ZERO = digital value corresponding to zero flow (125)

SW = small window, 5 digital units

LW = large window, 15 digital units

Digital values below ZERO are inspiratory flow, those above ZERO are expiratory flow.

Figure 3. Flow diagram of breath analysis section of the data collection and computation subroutine

```
RGE  CONTROL  VARIABLES
DATE 03/20/86          TIME 1406
NO. OF SAMPLES = 1250
SAMPLE FREQ.    = 65 HZ
SENSITIVITY SETTING = (5*.1)
 FLOW CONVER. EQTN.  Y = .66 X  -  82.4
INSP. O2 & CO2 CONC. = .209 , 0


RGE  ENVIRONMENTAL  VARIABLES
DATE 03/20/86          TIME 1406
AMBIENT TEMP = 298 K
BODY TEMP    = 312 K
BAROMETRIC PRESS. = 745 MMHG
VALVE DEAD SPACE  = .04 L


RGE  CALIBRATION  CONSTANTS
DATE 03/20/86          TIME 1406
CA1 (FLOW ZERO)=-125
CA2 (VOL CHECK)= 1002 ML
CA3 (X1 O2)= 250      CA4 (X2 O2)= 122
CA5 (X1 CO2)= 21      CA6 (X2 CO2)= 137
CA7 (LT O2)= .3112 SEC      CA9 (TC O2)= .0824 SEC
CA8 (LT CO2)= .3309 SEC     CA10 (TC CO2)= .1062 SEC
GA1 (CAL GAS %O2)= .148
GA2 (CAL GAS %CO2)= .047
O2 CONV EQTN %O2= 4.74E-04 X +  .0901
CO2 CONV EQTN %CO2= 4.04E-04 X + -8.7E-03


RESPIRATORY  GAS  EXCHANGE
DATE 03/20/86          TIME 1407

TIME   RR    TV     MV    VCO2    VO2     RQ     ETCO2   ETO2     VD    NB
HRMN  /MIN  ML/BR  ------ML/MIN-------          -----MMHG----     ML
             ----ATPD----  ----STPD----                           ATPD

------- DISK FILE: RGE 03/20 1005 -------
1400  18.8   170   3199     78      91    0.86    47.8    87.6     64     5
MITC  18.8   170   3199     61      82    0.75    47.8    87.6     80     5
NOGU  18.8   170   3199     59      84    0.71    50.1    86.4     82     5
```

Figure 4. Print-out of control and environmental variables, calibration constants, and respiratory function and gas exchange variables computed using the three different methods of compensation for the lag time and response of the gas analyzers

number of samples taken and the number of breaths that occurred during the sample period.

The graphics subroutine is used to display the sampled data on the monitor screen. The screen is divided into three horizontal sections. The flow, oxygen concentration, and carbon dioxide concentration signals are plotted in the same fashion as they appear on the physiological recorder trace. In addition, the points identified by the program as the beginning and end of expiration can be labeled on the screen. Likewise, the compensated gas concentration signals can also be displayed. The graphics subroutine provides a convenient means of visually checking the sampled data, the breath analysis (expiration identification) section of the program, and the compensation of the gas analyzer signals.

RESULTS

To test the program, simultaneous measurements of respiratory function and gas exchange were made using both the computer-based system and the traditional mixed-expired method. In addition, three different methods of compensation for the lag time and response of the analyzers were compared. Simultaneous computer-derived and mixed-expired respiratory function and gas exchange measurements were made on 8 dogs weighing from 11 to 25 kg. The dogs were intubated orally with a cuffed endotracheal tube and were maintained under pentobarbital anesthesia.

For mixed-expired measurements a mechanical flowmeter was attached to the inspiratory port of the breathing valve. Expired air samples were collected throughout the sample period in a bag attached to the expiratory port of the breathing valve. The mixed-expired samples were analyzed using the Beckman LB-2 carbon dioxide and OM-11 oxygen analyzers. The same analyzers were used for both the computer-derived and mixed-expired measurements in order to avoid differences resulting from the method of gas analysis. Gas exchange values were converted to STPD. Tidal volume and minute ventilation values were corrected to ATPD.

Initially, mixed-expired air samples were collected over a one to three minute period during which several measurements were made using the computer-based system (dogs #1 and #2). The computer-derived values were then averaged and compared with the values obtained using the mixed-expired method. However, although the dogs were generally stable there were small changes in respiratory function and presumably gas exchange over the course of the sample period. Consequently, the averaged computer-derived values were not always reflective of the entire sample period.

In order to obtain a better comparison, measurements were made using the same sample period for both methods (dogs #3 through #8). Thus, during the period when mixed-expired gas samples were being collected, approximately one minute, the computer was also collecting data. The time required for computation was increased significantly as a result of the long sample period, however, a better comparison of the two methods of measurement was obtained.

Three methods of compensating for lag time and response of the analyzers were compared. The three methods were the time delay compensation, the first-order compensation described by Mitchell (1979), and the first-order compensation described by Noguchi et al. (1982). Gas exchange values were computed and then recomputed using the same set of data and the three different methods of compensation for the lag time and response of the analyzers.

As expected the gas exchange values obtained using the first-order compensations described by Mitchell (1979) and Noguchi et al. (1982) were quite similar. A comparison of values obtained using both methods appears in Table 1. The gas exchange measurements presented in Table 1 were obtained from 3 different dogs. Because both methods yield almost identical results and the method employed by Noguchi et al. (1982) requires a considerable amount of extra computation, the first-order compensation described by Noguchi et al. (1982) was not was used in subsequent comparisons. Instead, only the simple time delay compensation and the first-order compensation described by Mitchell (1979) were used in subsequent comparisons of computer-derived and mixed-expired gas exchange values.

Table 1. Comparison of first-order methods of compensation for the lag time and response of the gas analyzers

	Mitchell's Method		Noguchi's Method	
DOG#	$\dot{V}CO_2$	$\dot{V}O_2$	$\dot{V}CO_2$	$\dot{V}O_2$
	----ml/min----		----ml/min----	
1	59	80	57	83
2	137	139	134	142
3	75	96	73	99

The results of the simultaneous measurements of respiratory function and gas exchange are listed in Table 2. One to three replicate measurements were obtained from each dog. After a substantial change in respiratory function, an additional set of measurements was obtained from dog #2. Thus, from a total of 8 dogs, 9 sets of measurements were obtained. Average computer-derived and mixed-expired values were calculated for each of the 9 sets of measurements.

Average computer-derived and mixed-expired values for minute ventilation ($\dot{V}_E$), carbon dioxide production ($\dot{V}CO_2$), and oxygen consumption ($\dot{V}O_2$) are plotted in Figures 5 through 9. The computer-derived gas exchange values that appear in Figures 6 and 7 were obtained using the simple time delay compensation for the lag time and response of the gas analyzers. The computer-derived gas exchange values that appear in Figures 8 and 9 were obtained using the first-order compensation described by Mitchell (1979). A best-fit least squares linear regression was performed for each comparison and the resulting regression line along with the linear equation, the correlation coefficient (R), and the number of dogs (N) used in the comparison appear in each figure.

The dogs' respiratory rates varied from 12 to 40 breaths/min. The difference between the computer-derived respiratory rates and the observed rates was usually limited to some small fraction of a breath per minute. The dogs' tidal volumes ranged from 200 to 300 ml, while computer-derived physiological dead space volumes ranged from 60 to 105 ml.

Table 2. Simultaneous measurements of respiratory function and gas exchange using the traditional mixed-expired method and the computer-based system, expired volumes are in ml/min (ATPD) and gas exchange values are in ml/min (STPD)

	MIXED-EXPIRED			COMPUTER					
				Time Delay Comp.			First-Order Comp.		
Dog#	$\dot{V}_E$	$\dot{V}CO_2$	$\dot{V}O_2$	$\dot{V}_E$	$\dot{V}CO_2$	$\dot{V}O_2$	$\dot{V}_E$	$\dot{V}CO_2$	$\dot{V}O_2$
1	3512	80	92	2864	78	97	----	---	---
	3140	57	62	3041	74	89	----	---	---
2	4794	124	126	4312	111	121	4312	108	116
	5086	125	124	4538	109	122	4538	104	116
	5318	127	127	5511	141	144	5511	137	139
	8776	133	145	9495	160	178	9495	152	169
	9190	138	139	9418	137	160	9418	129	151
	9746	145	143	9987	153	182	9987	144	171
3	4348	78	87	3929	73	86	3929	64	81
	4969	93	104	4563	85	101	4563	75	96
4	6890	118	111	6439	118	118	6439	101	107
	7734	119	118	7502	127	129	7502	106	114
5	4357	90	106	4257	90	115	4257	79	105
6	7993	111	112	8099	112	104	8099	95	107
	8661	118	121	8637	116	105	8637	98	108
7	6395	124	126	6005	114	115	6005	99	111
	5454	117	108	5168	91	108	5168	85	103
8	3153	98	99	3220	102	107	3220	92	111
	3134	102	102	3140	104	102	3140	96	106
$\bar{x}$[a]	6235	115	118	6131	114	123	6131	104	118
±SD[a]	2119	18	16	2299	24	27	2299	24	25
%[a]	----	--	--	1.7	0.9	4.2	1.7	9.6	0.0

[a] Mean ($\bar{x}$), standard deviation (SD), and percent deviation (%) values were computed using data from dogs #2 through #8. The percent deviation values were calculated as the differences between corresponding mixed-expired and computer-derived values as a percent of the mixed expired values. Data from dog #1 were not included because values for the first-order compensation were not available.

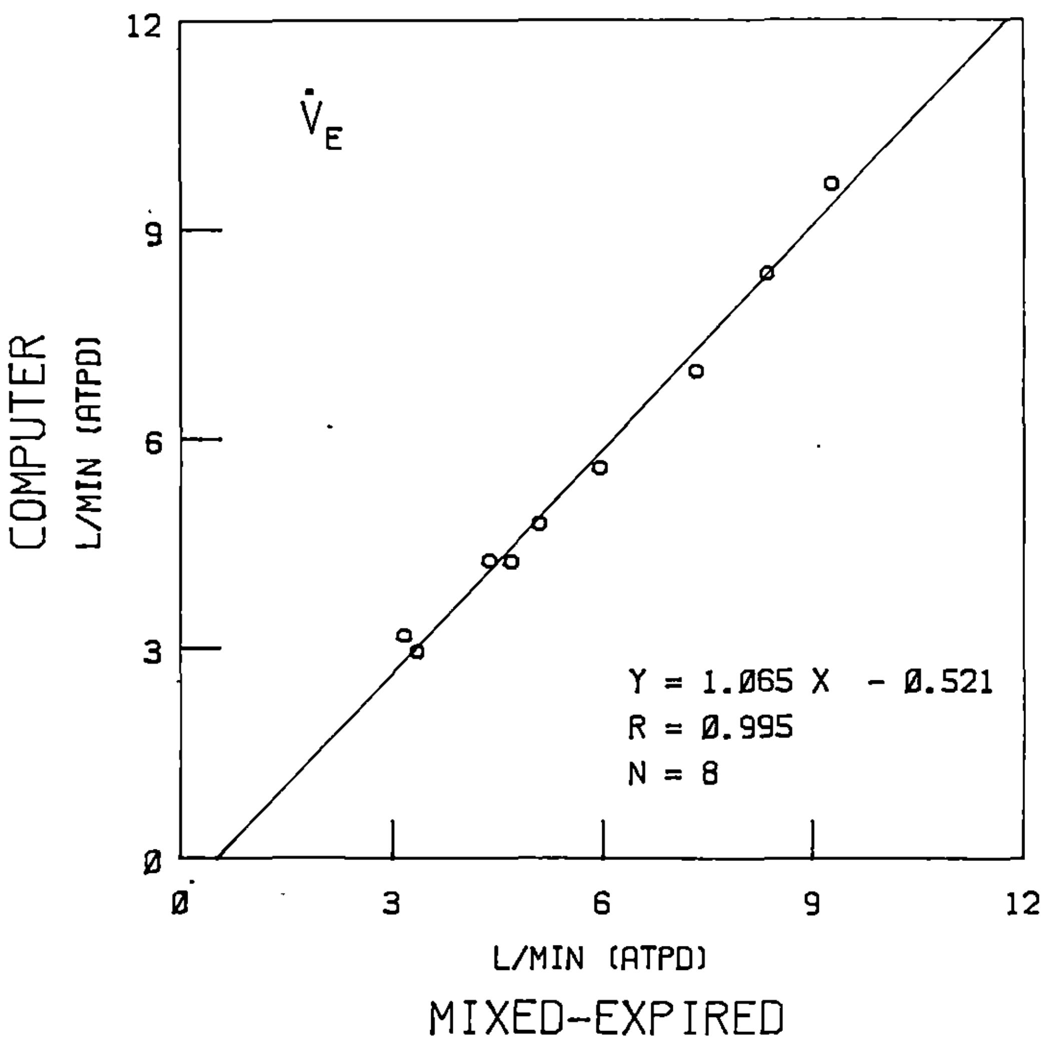


Figure 5. Comparison of minute ventilation measurements obtained using the traditional mixed-expired method and the computer-based system

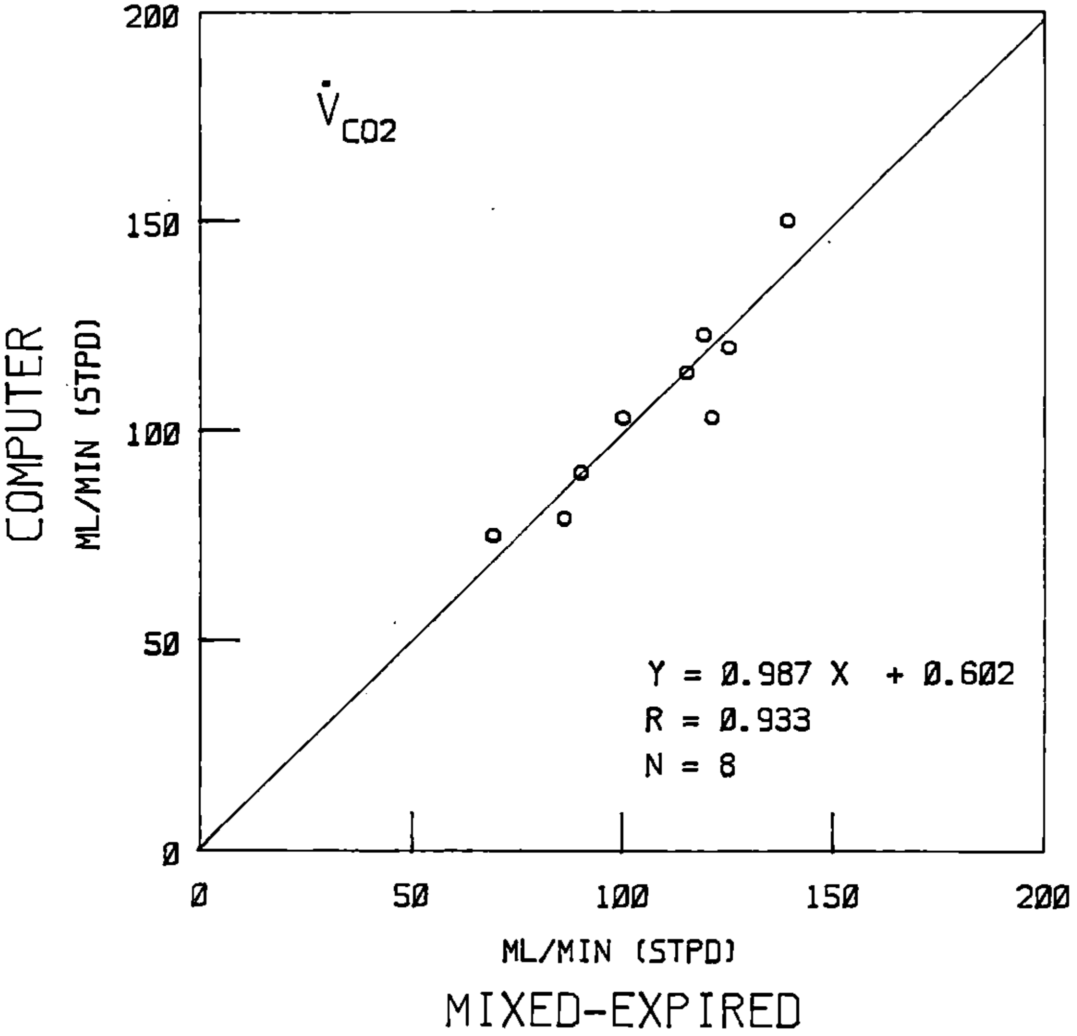


Figure 6. Comparison of carbon dioxide production measurements obtained using the traditional mixed-expired method and the computer-based system with a time delay correction for the lag time and response of the analyzer

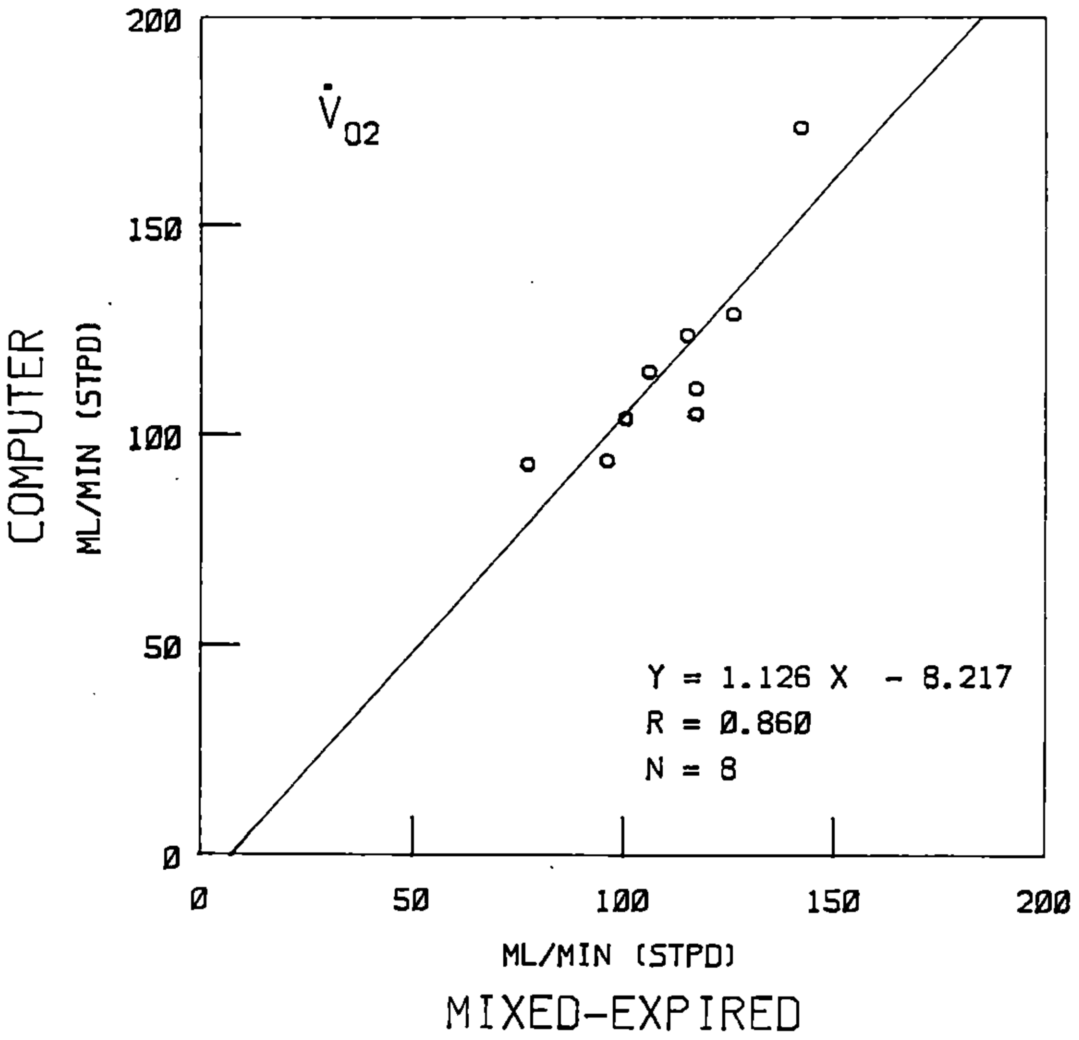


Figure 7. Comparison of oxygen consumption measurements obtained using the traditional mixed-expired method and the computer-based system with a time delay correction for the lag time and response of the analyzer

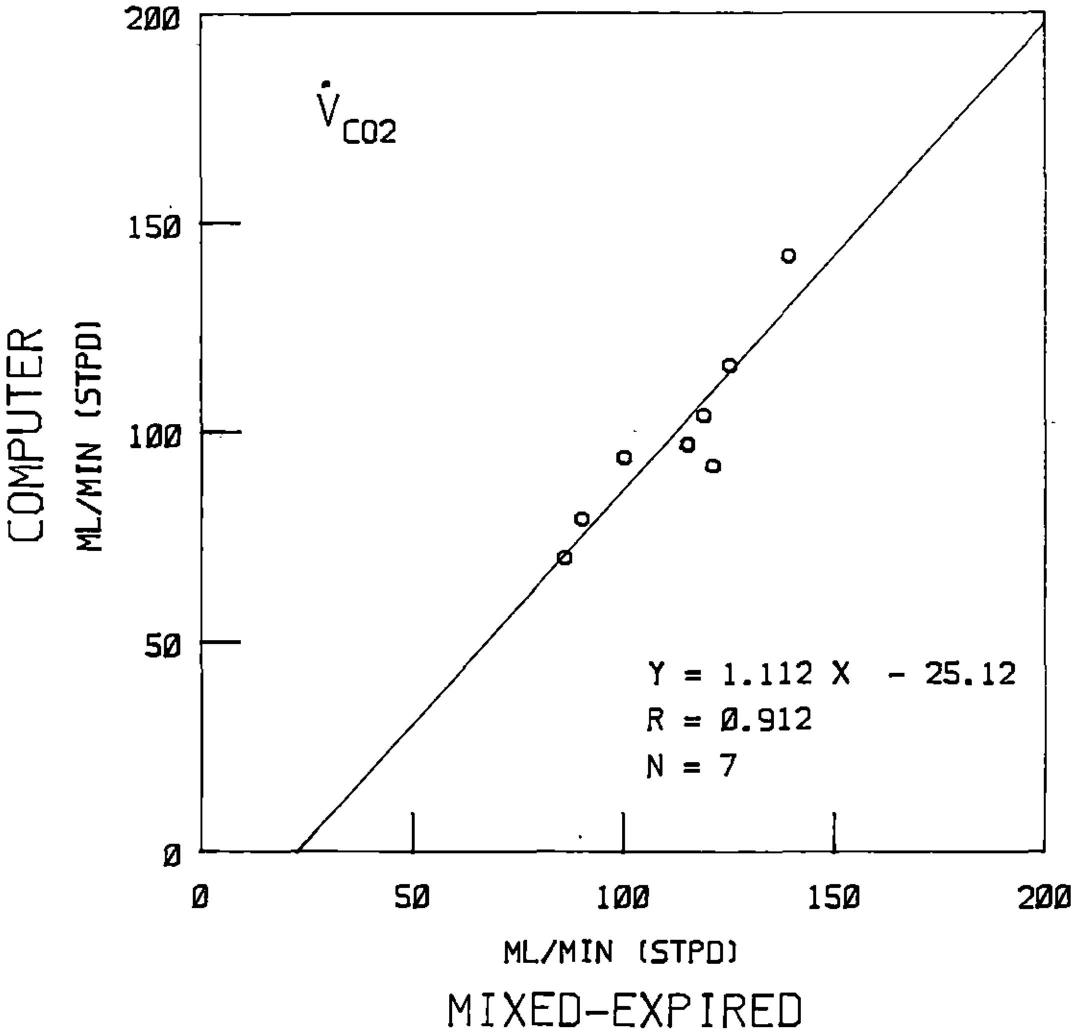


Figure 8. Comparison of carbon dioxide production measurements obtained using the traditional mixed-expired method and the computer-based system with a first-order compensation for the lag time and response of the analyzer

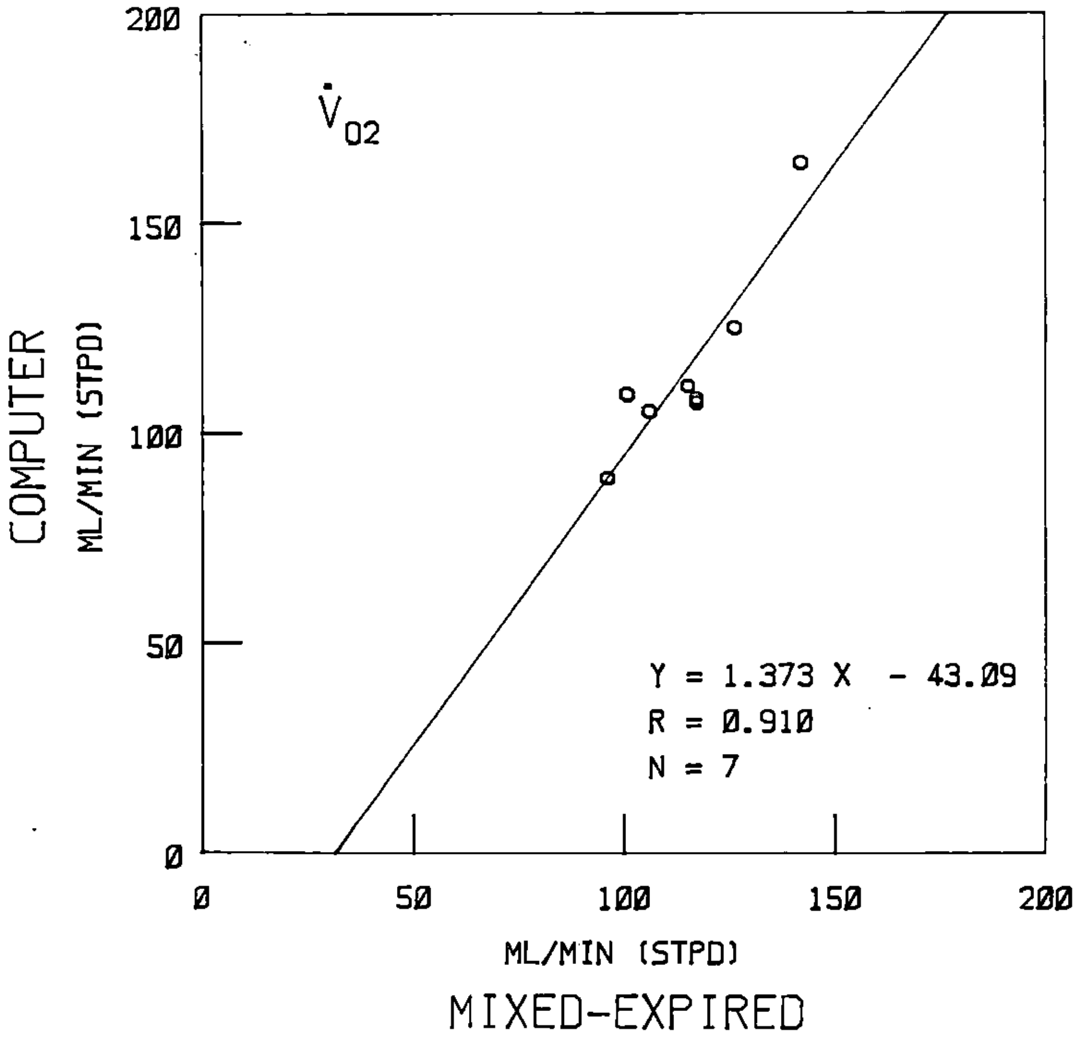


Figure 9. Comparison of oxygen consumption measurements obtained using the traditional mixed-expired method and the computer-based system with a first-order compensation for the lag time and response of the analyzer

DISCUSSION

Although the minute ventilation values obtained using the mechanical flowmeter tended to be larger than the computer-derived values, there was a very good correlation between corresponding values as shown in Figure 5. A small difference in the measured minute ventilations was expected because the mechanical flowmeter was measuring inspired volume while the computer-system was measuring expired volume. However, the difference between the inspired and expired minute ventilations should be equal to the difference between $\dot{V}O_2$ and $\dot{V}CO_2$, which was never greater than 20 ml (mixed-expired method) and therefore would not account for the larger differences that were observed.

A more probable explanation is that the mixed-expired minute ventilation values were over estimated as a result of air being pulled by the analyzers through the inspiratory port of the breathing valve and the attached mechanical flowmeter. The analyzers sampled air from the breathing valve at a rate of approximately 350 ml/min. Thus, between breaths when there should have been no flow through the breathing valve, the analyzers were probably pulling air through the mechanical flowmeter at a rate of 350 ml/min. As a result of the additional flow through the breathing valve, minute ventilation values obtained using the mechanical flowmeter would have been over estimated. This problem can be corrected by connecting a tube to the analyzer pump's exhaust port and returning the sampled gas back to the breathing valve.

There are a number of other factors which may have also contributed to the observed differences in the minute ventilation values. They include the assumptions and corrections used in converting the measurements to ATPD, the computer algorithms used in identifying and computing the expired volumes, and the linear conversion equation used in computing the expired volumes.

Of the two methods of compensation for the lag time and response of the analyzers, the simple time delay compensation provided the best agreement between computer-derived and mixed-expired gas exchange measurements (Figures 6 and 7). The reason why the first-order compensation yielded less favorable results is not clear (Figures 8 and 9). This method of compensation has been described by several investigators and has been incorporated into the design of many computer-based systems. Because the values computed using the first-order compensation are consistently lower than the corresponding mixed-expired values, a probable explanation would be that the transport delays or time constants of the analyzers were underestimated. Identifying the source of error is complicated by the fact that both the transport delays and the time constants are important components of the compensation equation and the compensation procedure is very sensitive to small errors in both these values.

Arieli and Van Liew (1981) found that the method used to measure the lag time and time constants can have a significant effect on the computed values. Mitchell (1979) computed the time constant as the absolute value of the slope of the logarithm of the normalized analyzer step response between 70 and 10% of the maximum response. In this project, the analyzer time constants were computed as the time between the beginning of the analyzers output response and the time the output reaches 63% of maximum response. Thus, a modification of the method used in this project to estimate lag times and time constants might improve the accuracy of gas exchange values computed using the first-order compensation. This problem deserves further investigation.

In contrast to the more complex first-order compensation, the simple time delay compensation proved to be effective while at the same time requiring a minimum amount of additional computation. Overall, the computer-derived values obtained using the simple time delay compensation correlate well with simultaneous mixed-expired measurements, Figures 6 and 7. Unfortunately, the computed gas exchange values were limited to a fairly small range. The regression equations and correlation coefficients would most likely be improved if a wider range of values were to be compared.

Although the computer-derived physiological dead space volumes, which ranged from 60 to 105 ml, were not verified directly, they do compare well with reported values. Severinghaus (1971) reported physiological dead space volumes ranging from 60 to 100 ml at tidal volumes of approximately 200 ml. The measurements were obtained from mechanically ventilated dogs weighing from 8 to 12 kg.

As a note, the computer-derived measurement of physiological dead space volume tends to be reflective of the quality of the gas exchange measurements. This relationship results from the fact that the physiological dead space volume is computed directly from the computer-derived $\dot{V}CO_2$. Thus, if the computed physiological dead space volume appears unreasonable, the gas exchange values should be suspect.

CONCLUSIONS

As stated in the introduction, the purpose of this project was to implement a flexible, low-cost, microcomputer-based system for on-line breath-by-breath analysis of respiratory function and gas exchange. In addition, the system was to be directed at research and possibly clinical applications involving animals. These goals have been acheived. A flexible, low-cost system for on-line breath-by-breath analysis of respiratory function and gas exchange has been developed. Furthermore, the computer-based system has been validated in a comparison of simultaneous computer-derived and traditional mixed-expired measurements obtained from anesthetized dogs.

Several compromises were made in order to simplify the required computation and instrumentation. The most important compromise was the use of only the expiratory phase of the respiratory cycle in computing respiratory function and gas exchange values. Because only the expiratory phase is used in the computations, gas exchange values should be averaged over several breaths in order to avoid errors resulting from changes in lung gas storage. For most applications, this is not a disadvantage and is still superior to the mixed-expired method with respect to the identification of transient changes in gas exchange.

Another result of using only the expiratory phase of the respiratory cycle to compute gas exchange is that the inspired concentration of carbon dioxide should be negligible and the inspired concentration of oxygen must be known and constant. Once again, for most applications this requirement is not of any consequence and as long as the concentration of oxygen in the inspired air is known, different gas mixtures can be used.

Despite these minor limitations the system is quite flexible and fairly simple to use. The calibration procedure can be completed in approximately 15 to 30 minutes. With respect to time and effort, there is a tremendous savings over the traditional mixed-expired method. As a result, the investigator is free from the task of collecting and analyzing expired samples and hand calculating the results. If additional computation speed is required, the BASIC program can be compiled. The compiled program runs several times faster than the uncompiled version. Using the compiled program, data from a 20 second sample period can be processed in approximately ten seconds. Thus, new respiratory function and gas exchange values can be computed and printed out at rates up to two or three times per minute.

As stated, the present system could be improved by simply moving the pneumotachograph to the expiratory port of the breathing valve. Some benefit might also arise from a more detailed investigation of the different methods of compensation for the lag time and response of the analyzers and an investigation of the different methods used to estimate the analyzer lag times and time constants. With respect to flexibility, the system could be modified for use without a physiological recorder. Since the analyzers have 0 to 5 V outputs they can be connected directly to the input/output board's analog-to-digital converter. However, if the same pneumotachograph/differential pressure transducer unit were to be used, additional analog circuits for balancing the differential pressure transducer and amplifying the flow signal would be required.

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APPENDIX A: OPERATOR CONTROL SUMMARY

Equipment Preparation

1. The gas analyzers and physiological recorder should be warmed-up for at least two hours.

2. After the instruments have been warmed-up, the gas analyzers should be calibrated and the physiological recorder should be adjusted.

   A. Analyzer calibration (for more detail see the instruction manuals)

      1. Room air
         a. While sampling room air through a drying tube, adjust the OM-11 oxygen analyzer GAIN until the analyzer reads 20.9%. Similarly, adjust the LB-2 carbon dioxide analyzer ZERO until the analyzer reads 0.00% (0.03% if carbon dioxide is not being scrubbed from the air passing through the drying tube).
      2. Calibration gas
         a. While sampling the calibration gas (approximately 5% CO2 and 15% O2), adjust the oxygen analyzer GAIN until the analyzer reading equals the concentration of oxygen in the calibration gas. Similarly, adjust the carbon dioxide analyzer GAIN until the analyzer reading equals the concentration of the carbon dioxide in the calibration gas.
      3. Repeat parts 1 and 2 several times to insure proper adjustment.

   B. Beckman recorder adjustment

      1. Balance the flow channel and center the pen.
      2. While sampling room air adjust the pens on the oxygen and carbon dioxide concentration channels one half centimeter from the top of the trace and one half centimeter from the bottom of the trace, respectively.
      3. The selection of recorder preamplifier and multiplier settings is based on the range of flow and gas concentrations expected during the course of the experiment. Normal settings for the flow channel are (5*0.1) or (2*0.1). Normal settings for the oxygen and carbon dioxide analyzer channels are (.5*1.0) and (1*1.0), respectively.

Loading the Program

1. The main program, assembly language sampling program, and the accessory data files which contain the environmental variables, control variables, and calibration constants are stored on a 5.25 inch floppy disk. The names of the respective files are RGE 1.00, SUPER SMPLR.ML, ENVR-VAR, CONT-VAR, and CAL-CONST.

A. The main program can be loaded and run using the RUN command as follows. `RUN "RGE 1.00" <RETURN>`

B. The assembly language sampling program and the accessory data files are automatically loaded by the main program. The sampling program is loaded into memory at addresses 1300H to 1399H.

Running the Program

1. The program is menu driven, and therefore, relatively easy to operate. The user is prompted by the program when data entry or a selection is required.

2. The calibration subroutine should be run before each experiment or after any changes are made in the Beckman recorder's sensitivity settings. The program provides a step-by-step procedure for obtaining the necessary calibration data.

   A. Initially, the entire calibration subroutine should be performed. However, each section of the subroutine can be run separately. For example, if during the course of an experiment the flow signal drifts, a new flow zero can be determined without having to repeat the entire calibration procedure.

3. The program can be stopped, started, listed, or if necessary edited at any time.

APPENDIX B: PROGRAM LISTING

MAIN PROGRAM

```
100 REM A$="RGE 1.00":SAVE"@0:"+A$,8:VERIFYA$,8
110 REM
120 REM ON-LINE BREATH-BY-BREATH ANALYSIS OF
130 REM RESPIRATORY FUNCTION AND GAS EXCHANGE
140 REM PHILLIP D. BAKER, 3/20/86
150 REM BIOMEDICAL ENGINEERING PROGRAM
160 REM IOWA STATE UNIVERSITY
170 REM
180 REM SET ERROR TRAP AND LOAD ASSEMBLY LANGUAGE SAMPLING PROGRAM
190 REM
200 FAST
210 TRAP 7830:REM IF ERROR OCCURS PROGRAM GOES TO LINE LISTED
220 IFPEEK(4886)<>173THENBLOAD"SUPER SMPLR.ML",D0,U8,B0,P4864
230 REM
240 REM DEFINE FUNCTIONS, INITIALIZE VARIABLES, AND DIMENSION ARRAYS
250 REM
260 REM FLOW, CO2 AND O2 CONVERSION EQUATIONS
270 DEF FNF(F)=((F+(124+CA(1)))*M(3)-B(3))/60
280 DEF FNC(C)=(M(2)*C+B(2)):REM CO2 CONVERSION EQUATION
290 DEF FNO(O)=(M(1)*O+B(1)):REM O2 CONVERSION EQUATION
300 REM PH2O AT 100% SAT FOR GIVEN TEMP (K)
310 DEF FNPW(T)=3161-22.45*T+.04*T*T
320 REM ROUND-OFF EQUATIONS
330 DEF FNR(R)=(INT(R+.5))
340 DEF FNR2(R)=(INT(1E2*R+.5))/1E2
350 DEF FNR4(R)=(INT(1E4*R+.5))/1E4
360 DEF FNR6(R)=(INT(1E6*R+.5))/1E6
370 REM
380 A=0:A0=0:A1=0:A2=0:A3=0:A4=0:A5=0:A6=0:A7=0:A8=0:A9=0:BP=0
390 C=0:CT=0:D2=0:D3=0:D4=0:DT=0:ET=0:HI=0:IT=0:K1=0:K2=0:K3=0
400 K4=0:LO=0:LL=0:LT=0:MN=0:MX=0:N=0:NB=0:O1=0:O2=0:PA=0:PB=0
410 PI=0:PS=0:RR=0:TA=0:TB=0:TE=0:TS=0:TV=0:TX=0:T1=0:T2=0:V=0
420 VC=0:VD=0:VO=0:W=0:X=0:XS=0:Y=0:YS=0:Z=0
430 REM
440 A$="":F$="":F1$="":F2$="":BP$=CHR$(7):CH$=CHR$(19):CS$=CHR$(147)
450 DN$=CHR$(17):ID$=CHR$(20):R$=CHR$(13):RF$=CHR$(146):RN$=CHR$(18)
460 UP$=CHR$(145)
470 REM
480 DIM D%(2,3000),E%(3,3000),B(3),C(240),CA(12),CH(3),E(5),ET(2)
490 DIM GA(2),L(50),LT(4),M(3),Q(9),TE(2),X(10),ZE(2)
500 REM
510 REM ADDRESS OF A/D CHANNELS TO BE SAMPLED
520 REM CH(1)=FLOW, CH(2)=%O2, CH(3)=%CO2
530 REM (57088 IS THE BASE ADDRESS FOR THE A/D CONVERTER)
540 REM
550 A=57088:CH(1)=A+1:CH(2)=A+6:CH(3)=A+7
560 GOTO 650
570 REM
580 REM SOUND SUBROUTINE
```

```
590 REM
600 VOL6:SOUND 1,4096,10
610 VOL5:SOUND 1,8192,5:RETURN
620 REM
630 REM SET SCREEN COLOR, ENTER DATE AND TIME
640 REM
650 PRINT CS$"    ON-LINE BREATH-BY-BREATH ANALYSIS"
660 PRINT TAB(9)"OF RESPIRATORY FUNCTION"
670 PRINT TAB(13)"AND GAS EXCHANGE"
680 PRINT TAB(6)"BIOMEDICAL ENGINEERING PROGRAM"
690 PRINT TAB(10)"IOWA STATE UNIVERSITY"
700 GRAPHIC1,1:COLOR 0,7:COLOR 1,2:COLOR4,7:COLOR 5,2:GRAPHIC0
710 SLOW
720 PRINT DN$DN$DN$:INPUT " DATE: MONTH/DAY/YEAR";DA$
730 PRINT DN$TAB(15)TI$UP$:INPUT" TIME: HRMNSC";TI$
740 REM
750 REM RESPIRATORY FUNCTION AND GAS EXCHANGE
760 REM
770 L$="RESPIRATORY GAS EXCHANGE":GOSUB4150
780 REM FLAGS 0=RESET, 1=SET, OR AS DEFINED
790 REM IF FL(1)=1, SKIP THE DISPLAY OF CALIBRATION CONSTANTS
800 REM IF FL(2)=N, COMPUTE GAS EXCHANGE N TIMES BEFORE STOPING
810 REM IF FL(3)=1, DO NOT PRINT HEADING ON OUTPUT TO THE PRINTER
820 REM IF FL(4)=1, GRAPH GAS CONC SIGNALS CORRECTED FOR LT AND RESP
830 REM IF FL(5)=0, CNTRL AND ENVR VARIABLES MUST BE ENTERED
840 REM IF FL(6)=1, INDICATE RECOMPUTED VALUES "MITC" (FL(6))
850 REM IF FL(7)=1,  "NOGU" (FL(7)) ON THE OUTPUT TO THE PRINTER
860 REM IF FL(8)=1, DATA HAS BEEN LOADED FROM DISK
870 REM IF FL(9)=1, GRAPH LAG TIME AND TIME CONST FROM CAL SUBROUTINE
880 FOR X=1TO9:FL(X)=0:NEXT
890 REM ENTER CONTROL & ENVIRONMENTAL VARIABLES
900 GOSUB 4220:GOSUB 4620
910 PRINT CS$:L$="RESPIRATORY GAS EXCHANGE":GOSUB 4150
920 REM
930 REM RGE PRIMARY MENU
940 REM
950 PRINT BP$" "RN$" 1 "RF$"  A/D CONV CHANNELS 1-8"
960 PRINT DN$" "RN$" 2 "RF$"  CALIBRATION SUBROUTINE"
970 PRINT DN$" "RN$" 3 "RF$"  COLLECT NEW DATA"
980 PRINT DN$" "RN$" 4 "RF$"  LOAD STORED DATA"
990 PRINT DN$" "RN$" 5 "RF$"  CHANGE CNTRL OR ENVR VARIABLES"
1000 GETKEY A$:V=VAL(A$):IF V<1 OR V>5 THEN 1000:ELSE GOSUB 610
1010 IF V=4 THEN PRINT UP$UP$UP$"  4 "DN$DN$DN$DN$
1020 IF V=5 THEN PRINT UP$"  5 "DN$DN$
1030 ON V GOTO 1080,5600,1040,1160,900
1040 IF FL(1)=1 THEN 1410:ELSE 7230
1050 REM
1060 REM A/D CONV AND DISPLAY CHAN 1-8
1070 REM
1080 L$="A/D CONVERSION CHANNELS 1-8":GOSUB 4150
1090 PRINT " CHAN#"TAB(9)"DATA"
```

```
1100 FOR N=0 TO 7:POKE A+N,0
1110 PRINT "  "N+1TAB(13)ID$ID$ID$ID$PEEK(A+N):NEXT
1120 PRINT DN$DN$" TYPE "RN$"RETURN"RF$" FOR OPENING MENU"
1130 PRINT CH$DN$DN$DN$DN$DN$DN$
1140 GET A$:IF A$=CHR$(13) THEN GOSUB 610:GOTO 910:ELSE 1100
1150 REM
1160 REM LOAD DATA FROM DISK
1170 REM
1180 FL(8)=1
1190 DIRECTORY D0,U8,"RGE*":REM LIST ALL FILES WITH PREFIX RGE
1200 REM CHECK FOR DISK ERRORS
1210 GOSUB 7860:IF DS=62 OR DS=74 THEN 910
1220 PRINT BP$DN$:INPUT " FILENAME";F$
1230 OPEN 2,8,2,"0:"+F$+",SEQ,R"
1240 GOSUB 7860:IF DS=62 OR DS=74 THEN CLOSE2:GOTO 910
1250 PRINT UP$" LOADING   "F$:GOSUB 600
1260 FAST
1270 INPUT#2,Q(0),DT
1280 FOR X=1 TO Q(0):FOR N=0 TO 2:INPUT#2,D%(N,X):NEXT:NEXT
1290 FOR X=1 TO 10:INPUT#2,CA(X):NEXT
1300 FOR X=1 TO 3:INPUT#2,B(X),M(X):NEXT:INPUT#2,GA(1),GA(2)
1310 FOR X=1 TO 9:INPUT#2,Q(X):NEXT
1320 FOR X=0 TO 3:INPUT#2,E(X):NEXT:CLOSE2
1330 PRINT UP$" LOADED  "DN$
1340 SLOW
1350 REM SUBR'S FOR CHANGING CNTRL AND ENVRN VARIABLES
1360 GOSUB 4260:GOSUB 4660
1370 FAST:GOTO 1630:REM PROCESS DATA LOADED FROM DISK
1380 REM
1390 REM COLLECT NEW DATA
1400 REM
1410 PRINT CS$DN$" "RN$"SAMPLING MODE"
1420 FOR CT=0 TO 10:X(CT)=0:NEXT
1430 PRINT BP$DN$" "RN$" 1 "RF$"  AUTOMATIC"
1440 PRINT DN$" "RN$" 2 "RF$"  MANUAL"
1450 PRINT DN$" "RN$" 3 "RF$"  SPECIFIC NUMBER"
1460 GETKEY A$:V=VAL(A$):IF V<1 OR V>3 GOTO 1460:ELSE GOSUB 610
1470 IF V=1 THEN FL(2)=10:GOTO 1550
1480 IF V=2 THEN FL(2)=0:GOTO 1550
1490 PRINT UP$UP$UP$"  3  "DN$DN$DN$
1500 PRINT BP$;:INPUT" ENTER NUMBER OF TIMES TO REPEAT";FL(2)
1510 REM
1520 REM WAIT FOR A BREATH, THEN BEGIN COLLECTING DATA (THE ASSEMBLY
1530 REM LANGUAGE SAMPLING PROGRAM IS STORED AT ADDRESSES 1300H TO 1399H)
1540 REM
1550 FL(2)=FL(2)-1:PRINT CS$DN$" "RN$"WAITING FOR BREATH"
1560 GOSUB 5010:REM INITIALIZE ASSEMBLY LANGUAGE SAMPLING PROGRAM
1570 LW=-CA(1)-10:UW=-CA(1)+10:REM SET WINDOW
1580 POKE CH(1),0:IF PEEK(CH(1))<LW THEN 1580
1590 POKE CH(1),0:IF PEEK(CH(1))>UW THEN 1590
1600 PRINT CS$DN$" "RN$"COLLECTING DATA"
```

```
1610 GOSUB 600:T1=TI:SYS4886:T2=TI-T1:GOSUB 600:DT=T2/(Q(0)*60)
1620 REM LT(1), LT(2) = LAG TIMES OF THE O2 & CO2 ANALYZERS
1630 FAST:LT(1)=FNR((CA(7)+CA(9))/DT):LT(2)=FNR((CA(8)+CA(10))/DT)
1640 REM
1650 REM IDENTIFY INSPIRATION AND EXPIRATION FOR EACH BREATH
1660 REM
1670 IF LT(1)>LT(2) THEN LT=LT(1):ELSE LT=LT(2)
1680 X=1:Y=0:Z=1:D2=.75/DT:D3=-Q(3)-CA(1):D4=Q(3)-CA(1)
1690 FOR CT=1 TO Q(0)-LT STEP 2
1700 ON Z GOTO 1710,1730,1750,1780,1810,1820,1830
1710 IF D%(0,CT)>D3 THEN Z=2
1720 GOTO 1890
1730 IF D%(0,CT)<D3 THEN 1850
1740 GOTO 1890
1750 IF (D%(0,CT)+CA(1))<-15 THEN Z=5
1760 IF CT>C(X)+D2 THEN Z=1:X=1
1770 GOTO 1890
1780 IF (D%(0,CT)+CA(1))>15 THEN Z=7
1790 IF CT>C(X)+D2 THEN Z=1:X=1
1800 GOTO 1890
1810 IF D%(0,CT)>D3 THEN 1840:ELSE 1890
1820 IF D%(0,CT)<D4 THEN 1890:ELSE 1840
1830 IF D%(0,CT)>D4 THEN 1890
1840 Y=Y+1:ON Y GOTO 1860,1870,1880
1850 Z=3:C(X)=CT-1:GOTO 1890
1860 Z=6:X=X+1:C(X)=CT+1:GOTO 1890
1870 Z=4:X=X+1:C(X)=CT-1:GOTO 1890
1880 Z=2:X=X+1:C(X)=CT+1:X=X+1:Y=0
1890 NEXT:NB=INT(X/4):IF NB=0 THEN SLOW:GOTO 1550
1900 IF NB=1 THEN RR=0:GOTO 2020
1910 REM
1920 REM RESPIRATORY RATE, RR (BREATHS/MIN)
1930 REM
1940 RR=(NB-1)*60/((C(NB*4)-C(4))*DT)
1950 REM
1960 REM COMPUTE RESPIRATORY FUNCTION AND GAS EXCHANGE VARIABLES
1970 REM USING THE SINGLE TIME DELAY COMPENSATION FOR THE LAG TIME
1980 REM AND RESPONSE OF THE GAS ANALYZERS. THE TIME DELAYS FOR THE
1990 REM ANALYZERS, LT(1) & LT(2), ARE THE SUM OF THE ANLYZERS LAG
2000 REM TIME PLUS ONE TIME CONSTANT.
2010 REM
2020 VC=0:VO=0:VD=0:TE(1)=0:TE(2)=0:ET(1)=0:ET(2)=0:E1=255:E2=0:VT=0:TV=0
2030 FOR X=3 TO NB*4 STEP 4:T1=C(X):T2=C(X+1)
2040 FOR CT=T1 TO T2
2050 REM END TIDAL VALUES, ETO2 AND ETCO2
2060 IF D%(1,CT+LT(1)) < E1 THEN E1=D%(1,CT+LT(1))
2070 IF D%(2,CT+LT(2)) > E2 THEN E2=D%(2,CT+LT(2))
2080 REM VO2, VCO2, AND VT (RECTANGLE RULE OF INTEGRATION)
2090 TE(1)=TE(1)+FNF(D%(0,CT))*FNO(D%(1,CT+LT(1)))*DT
2100 TE(2)=TE(2)+FNF(D%(0,CT))*FNC(D%(2,CT+LT(2)))*DT
2110 VT=VT+FNF(D%(0,CT))*DT
```

```
2120 NEXTCT
2130 TV=TV+VT
2140 TE=TE(2)-FNC(E2)*E(3)*TA/TX
2150 VC=VC+TE
2160 VO=VO+(Q(8)*(VT*K5-TE-E(3)*K4)+FNO(E1)*E(3)*TA/TX-TE(1))/(1-Q(8))
2170 VD=VD+VT-TE/FNC(E2)-E(3)*TA/TX
2180 ET(1)=ET(1)+E1:E1=255
2190 ET(2)=ET(2)+E2:E2=0
2200 VT=0:TE(1)=0:TE(2)=0:NEXTX
2210 ET(1)=FNO(ET(1)/NB)*BP:REM ETO2 MMHG
2220 ET(2)=FNC(ET(2)/NB)*BP:REM ETCO2 MMHG
2230 TV=(TV/NB)*K5:REM AVG TIDAL VOLUME (L) (ATPD)
2240 VC=VC*K1:REM VCO2 (L/MIN) (STPD)
2250 VO=VO*K1:REM VO2 (L/MIN) (STPD)
2260 VD=(VD/NB)*K5:REM AVG DEAD SPACE VOLUME (L) (ATPD)
2270 REM
2280 REM AVERAGE INSPIRATORY AND EXPIRATORY TIME
2290 REM
2300 IT=0:FOR X=1 TO NB*4 STEP 4:IT=C(X+1)-C(X)+IT:NEXT:IT=(IT/NB)*DT
2310 ET=0:FOR X=1 TO NB*4 STEP 4:ET=C(X+3)-C(X+2)+ET:NEXT:ET=(ET/NB)*DT
2320 FL(4)=0:GOTO 3250
2330 REM
2340 REM RECOMPUTE GAS EXCHANGE VARIABLES COMPENSATING FOR THE LAG TIME
2350 REM AND RESPONSE OF THE ANALYZERS USING METHOD DESCRIBED BY MITCHELL
2360 REM (BASED ON SINGLE-EXPONENT MODEL OF THE ANALYZER'S RESPONSE).
2370 REM
2380 FAST
2390 VC=0:VO=0:VD=0:TE(1)=0:TE(2)=0:ET(1)=0:ET(2)=0:E1=255:E2=0:VT=0:TV=0
2400 LT(3)=CA(7)/DT:LT(4)=CA(8)/DT:REM O2 AND CO2 DELAYS
2410 FOR X=3 TO NB*4 STEP 4
2420 FOR CT=C(X) TO C(X+1)
2430 REM END TIDAL VALUES, ETO2 AND ETCO2
2440 IF D%(2,CT+LT(2)) > E2 THEN E2=D%(2,CT+LT(2))
2450 IF D%(1,CT+LT(1)) < E1 THEN E1=D%(1,CT+LT(1))
2460 REM VO2, VCO2, AND VT (RECTANGLE RULE OF INTEGRATION)
2470 A1=CA(10)/DT:A2=FNC(D%(2,CT+LT(4)+1)):A3=FNC(D%(2,CT+LT(4)))
2480 A4=FNF(D%(0,CT))*DT:A5=(A1*(A2-A3)+A3)*A4
2490 TE(2)=TE(2)+A5
2500 A1=CA(9)/DT:A2=FNO(D%(1,CT+LT(3)+1)):A3=FNO(D%(1,CT+LT(3)))
2510 A4=FNF(D%(0,CT))*DT:A5=(A1*(A2-A3)+A3)*A4
2520 TE(1)=TE(1)+A5
2530 VT=VT+FNF(D%(0,CT))*DT
2540 NEXT
2550 TV=TV+VT
2560 TE=TE(2)-FNC(E2)*E(3)*TA/TX
2570 VC=VC+TE
2580 VO=VO+(Q(8)*(VT*K5-TE-E(3)*K4)+FNO(E1)*E(3)*TA/TX-TE(1))/(1-Q(8))
2590 VD=VD+VT-TE/FNC(E2)-E(3)*TA/TX
2600 ET(1)=ET(1)+E1:E1=255
2610 ET(2)=ET(2)+E2:E2=0
2620 VT=0:TE(1)=0:TE(2)=0::NEXTX
```

```
2630 ET(1)=FNO(ET(1)/NB)*BP:REM ETO2 (MMHG)
2640 ET(2)=FNC(ET(2)/NB)*BP:REM ETCO2 (MMHG)
2650 TV=(TV/NB)*((BP-PE)/BP):REM AVG TIDAL VOLUME (L) (ATPD)
2660 VC=VC*TS*BP/(TA*PS):REM VCO2 (L/MIN) (STPD)
2670 VO=VO*TS*BP/(TA*PS):REM VO2 (L/MIN) (STPD)
2680 VD=(VD/NB)*K5:REM AVG DEAD SPACE VOLUME (L) (ATPD)
2690 FL(4)=0:FL(6)=1:GOTO 3250
2700 REM
2710 REM RECOMPUTE GAS EXCHANGE VARIABLES COMPENSATING FOR THE LAG TIME
2720 REM AND RESPONSE OF THE ANALYZERS USING METHOD DESCRIBED BY NOGUCHI
2730 REM (BASED ON SINGLE-EXPONENT MODEL OF THE ANALYZER'S RESPONSE).
2740 REM
2750 PRINT TAB(24)FNR4(CA(7))UP$:INPUT "    O2 ANALYZER DELAY =";CA(7)
2760 PRINT TAB(24)FNR4(CA(9))UP$:INPUT "    O2 ANALYZER RESP. =";CA(9)
2770 PRINT TAB(25)FNR4(CA(8))UP$:INPUT "    CO2 ANALYZER DELAY =";CA(8)
2780 PRINT TAB(25)FNR4(CA(10))UP$:INPUT "    CO2 ANALYZER RESP. =";CA(10)
2790 REM
2800 REM 5 POINT MOVING AVERAGE FILTER
2810 REM
2820 FAST
2830 FOR N=1 TO 2:FOR X=5 TO Q(0)-5
2840 E%(N-1,X)=(D%(N,X-4)+D%(N,X-2)+D%(N,X)+D%(N,X+2)+D%(N,X+4))/5
2850 NEXT:NEXT
2860 REM
2870 REM COMPENSATION FOR ANALYZER TRANSPORT DELAY AND DYNAMIC RESPONSE
2880 REM
2890 LT(3)=CA(7)/DT:LT(4)=CA(8)/DT
2900 FOR N=0 TO 1:FOR X=3 TO Q(0)-LT(N+3)-2:TE=X+LT(N+3)
2910 E%(N+2,X)=E%(N,TE)+CA(9+N)*(E%(N,TE+1)-E%(N,TE))/DT
2920 NEXT:NEXT:GOSUB 610
2930 REM
2940 VC=0:VO=0:VD=0:TE(1)=0:TE(2)=0:ET(1)=0:ET(2)=0:E1=255:E2=0:VT=0:TV=0
2950 FOR X=3 TO NB*4 STEP 4
2960 FOR CT=C(X)+INT((C(X+1)-C(X))*.75) TO C(X+1)
2970 REM END TIDAL VALUES, ETO2 AND ETCO2
2980 IF E%(2,CT) < E1 THEN E1=E%(2,CT)
2990 IF E%(3,CT) > E2 THEN E2=E%(3,CT)
3000 NEXTCT
3010 FOR CT=C(X) TO C(X+1)
3020 REM VO2, VCO2, AND VT (RECTANGLE RULE OF INTEGRATION)
3030 TE(1)=TE(1)+FNO(E%(2,CT))*FNF(D%(0,CT))*DT
3040 TE(2)=TE(2)+FNC(E%(3,CT))*FNF(D%(0,CT))*DT
3050 VT=VT+FNF(D%(0,CT))*DT
3060 NEXTCT
3070 TV=TV+VT
3080 TE=TE(2)-FNC(E2)*E(3)*TA/TX
3090 VC=VC+TE
3100 VO=VO+(Q(8)*(VT*K5-TE-E(3)*K4)+FNO(E1)*E(3)*TA/TX-TE(1))/(1-Q(8))
3110 VD=VD+VT-TE/FNC(E2)-E(3)
3120 ET(1)=ET(1)+E1:E1=255
3130 ET(2)=ET(2)+E2:E2=0
```

```
3140 VT=0:TE(1)=0:TE(2)=0:NEXTX
3150 ET(1)=FNO(ET(1)/NB)*BP:REM ETO2 (MMHG)
3160 ET(2)=FNC(ET(2)/NB)*BP:REM ETCO2 (MMHG)
3170 TV=(TV/NB)*K5:REM AVG TIDAL VOLUME ((L) (ATPD)
3180 VC=VC*TS*BP/(TA*PS):REM VCO2 (L/MIN) (STPD)
3190 VO=VO*TS*BP/(TA*PS):REM VO2 (L/MIN) (STPD)
3200 VD=(VD/NB)*((BP-PE)/BP):REM AVG DEAD SPACE VOLUME (L) (ATPD)
3210 FL(4)=1:FL(7)=1:GOTO 3250
3220 REM
3230 REM PRINT DERIVED VALUES
3240 REM
3250 GOSUB 600:SLOW:L$="RESPIRATORY MEASUREMENTS":GOSUB 4150
3260 PRINT UP$" NO. OF SAMPLES ="Q(0)
3270 PRINT " SAMPLE FREQ    ="FNR(1/DT)" SAMPLES/SEC"
3280 PRINT " NO. OF BREATHS ="NB;DN$
3290 PRINT " AVG INSP TIME  ="FNR2(IT)" SEC/BREATH"
3300 PRINT " AVG EXP TIME   ="FNR2(ET)" SEC/BREATH"
3310 PRINT " RESP RATE      ="FNR(RR)" BREATHS/MIN"
3320 PRINT " TIDAL VOLUME   ="FNR(TV*1E3)" ML"
3330 PRINT " MINUTE VOLUME  ="FNR(TV*1E3*RR)" ML/MIN"
3340 PRINT " DEAD SPACE     ="FNR(VD*1E3)" ML (PHYSIOL)"DN$
3350 PRINT " VCO2  ="FNR(VC*1E3*RR/NB)" ML/MIN"
3360 PRINT " VO2   ="FNR(VO*1E3*RR/NB)" ML/MIN"
3370 PRINT " RQ    ="FNR2(VC/VO)
3380 IF FL(2)>=1 THEN 3430
3390 PRINT BP$DN$" PRINT MEASUREMENTS "RN$"(Y/N)"RF$
3400 GETKEY A$:IF A$<>"Y" AND A$<>"N" THEN 3400
3410 PRINT UP$" PRINT MEASUREMENTS (Y/N)"UP$UP$
3420 IF A$="N" THEN 3730
3430 T=RR*1E3:A0=RR:A1=TV*1E3:A2=TV*T:A3=VC*T/NB:A4=VO*T/NB
3440 IF A4=0 THEN A5=0:ELSE A5=A3/A4
3450 A6=ET(2):A7=ET(1):A8=VD*1E3:A9=NB
3460 REM
3470 REM PRINT HARD-COPY OF DERIVED VALUES
3480 REM
3490 IF FL(3)=1 THEN 3590:ELSE FL(3)=1
3500 OPEN 4,4:PRINT#4
3510 PRINT#4,CHR$(14)"RESPIRATORY GAS EXCHANGE"CHR$(15)
3520 PRINT#4,"DATE "DA$,"TIME "LEFT$(TI$,4):PRINT#4
3530 PRINT#4,"TIME    RR     TV      MV     VCO2     VO2     RQ     ";
3540 PRINT#4,"ETCO2    ETO2     VD    NB"
3550 PRINT#4,CHR$(17)"HRMN   /MIN   ML/BR    ------ML/MIN-------    ";
3560 PRINT#4,"        -----MMHG----     ML"
3570 PRINT#4,"              ----ATPD----    ----STPD----        ";
3580 PRINT#4,"                      ATPD":CLOSE 4
3590 IF FL(8)=0 THEN 3620
3600 OPEN 4,4:PRINT#4:PRINT#4,"------- DISK FILE: "F$" -------":CLOSE 4
3610 FL(8)=0
3620 OPEN 1,4,1:OPEN 2,4,2
3630 F1$="AAAA   99.9   9999   99999    9999    9999"
3640 F2$="    9.99    999.9   999.9   9999    99":F$=F1$+F2$:PRINT#2,F$
```

```
3650 IF FL(6)=1 THEN A$="MITC":GOTO3690
3660 IF FL(7)=1 THEN A$="NOGU":GOTO3690
3670 PRINT#1,TI$;CHR$(29);A0;A1;A2;A3;A4;A5;A6;A7;A8;A9:CLOSE 2:CLOSE 1
3680 GOTO 3700
3690 PRINT#1,A$;CHR$(29);A0;A1;A2;A3;A4;A5;A6;A7;A8;A9:GOTO 3730
3700 X(0)=X(0)+A0:X(1)=X(1)+A1:X(2)=X(2)+A2:X(3)=X(3)+A3:X(4)=X(4)+A4
3710 X(5)=X(5)+A5:X(6)=X(6)+A6:X(7)=X(7)+A7:X(8)=X(8)+A8:X(9)=X(9)+A9
3720 X(10)=X(10)+1
3730 CLOSE 1:CLOSE 2:FL(6)=0:FL(7)=0:FL(8)=0
3740 GET A$:IF FL(2)>=1 AND A$="" THEN 1550:ELSE FL(2)=0
3750 GOSUB 600:L$="RESPIRATORY MEASUREMENTS":GOSUB 4150
3760 PRINT BP$DN$" "RN$" 1 "RF$"  CONTINUE SAMPLING ROUTINE"
3770 PRINT DN$" "RN$" 2 "RF$"  RETURN TO OPENING MENU"
3780 PRINT DN$" "RN$" 3 "RF$"  STORE DATA"
3790 PRINT DN$" "RN$" 4 "RF$"  GRAPH DATA"
3800 PRINT DN$" "RN$" 5 "RF$"  RECALCULATE
3810 GETKEY A$:V=VAL(A$):IF V<1 OR V>5 THEN 3810:ELSE GOSUB 610
3820 ON V GOTO 1550,3900,4000,3830,3840
3830 GOSUB5150:GOTO3250
3840 PRINT CS$DN$" "RN$"RECALCULATION"
3850 PRINT DN$" "RN$" 1 "RF$"  MITCHELL 1ST ORDER RESP"
3860 PRINT BP$DN$" "RN$" 2 "RF$"  NOGUCHI 1ST ORD RESP"
3870 GETKEY A$:V=VAL(A$):IF V<1 OR V>2 THEN 3870:ELSE GOSUB 610
3880 IF V=2 THEN PRINT UP$"  2 "DN$
3890 ON V GOTO 2380,2750
3900 PRINT BP$CS$DN$" PRINT AVERAGE "RN$"(Y/N)"
3910 GETKEY A$:PRINT UP$TAB(15)"(Y/N)"
3920 IF A$="N" THEN 910
3930 OPEN 1,4,1:OPEN 2,4,2:PRINT#2,F$:PRINT#1,R$;"AVG";CHR$(29);
3940 FOR X=0 TO 9:PRINT#1,X(X)/X(10);:NEXT
3950 PRINT#1,R$:CLOSE 1:CLOSE 2
3960 GOTO 910
3970 REM
3980 REM STORE DATA TO DISK
3990 REM
4000 F$="RGE "+DA$+" "+LEFT$(TI$,4)
4010 PRINT UP$UP$UP$UP$UP$"  3  "RN$"SAVING FILE"RF$":"F$DN$DN$DN$DN$
4020 F$="0:"+F$+",SEQ,W":OPEN 2,8,2,F$
4030 REM CHECK FOR DISK ERRORS
4040 GOSUB 7860:IF DS=62 OR DS=74 THEN CLOSE2:GOTO 3750
4050 PRINT#2,Q(0);R$;DT
4060 FOR X=1 TO Q(0):FOR N=0 TO 2:PRINT#2,D%(N,X):NEXT:NEXT
4070 FOR X=1 TO 10:PRINT#2,CA(X):NEXT
4080 FOR X=1 TO 3:PRINT#2,B(X);R$;M(X):NEXT:PRINT#2,GA(1);R$;GA(2)
4090 FOR X=1 TO 9:PRINT#2,Q(X):NEXT:FOR X=0 TO 5
4100 FOR X=0 TO 5:PRINT#2,E(X):NEXT:CLOSE 2
4110 GOTO3750
4120 REM
4130 REM HEADLINES SUBROUTINE
4140 REM
4150 LL=LEN(L$):LT=(38-LL)/2:PRINT CS$
```

```
4160 PRINT TAB(LT)"┌";:FOR X=1 TO LL:PRINT "├";:NEXT
4170 PRINT "┌":PRINT TAB(LT);"┬";L$;"┬":PRINT TAB(LT);"⊥";
4180 FOR X=1 TO LL:PRINT "├";:NEXT:PRINT "┬"DN$DN$:RETURN
4190 REM
4200 REM CONTROL VARIABLES SUBROUTINE
4210 REM
4220 OPEN 2,8,2,"0:CONT-VAR,SEQ,R"
4230 FOR X=0 TO 9:INPUT#2,Q(X):NEXT:CLOSE 2
4240 REM CHECK FOR DISK ERRORS
4250 GOSUB 7860:IF DS=62 OR DS=74 THEN 4220
4260 PRINT BP$" CHANGE CONTROL VARIABLES "RN$"(Y/N)"
4270 PRINT "                                "UP$
4280 GETKEY A$:IF A$<>"Y" AND A$<>"N" THEN 4280
4290 PRINT UP$TAB(26)"(Y/N)"
4300 IF A$="N" AND FL(5)=1 THEN 4580
4310 PRINT TAB(17)Q(0)UP$:INPUT "  NO. OF SAMPLES";Q(0)
4320 PRINT TAB(20)Q(2)UP$:INPUT "  SAMPLE FREQUENCY ";Q(2)
4330 PRINT TAB(23)Q(3)UP$:INPUT "  INSP & EXP THRESHOLD";Q(3)
4340 PRINT "  FLOW CONV EQTN (SLOPE & INTERECEPT)"
4350 PRINT TAB(21)Q(4)","Q(5)UP$
4360 INPUT "    1) SETTING (2*.1)";Q(4),Q(5)
4370 PRINT TAB(21)Q(6)","Q(7)UP$
4380 INPUT "    2) SETTING (5*.1)";Q(6),Q(7)
4390 PRINT TAB(36)"2"UP$
4400 INPUT "   FLOW SENSITIVITY SETTING 1 OR 2";A$
4410 V=VAL(A$):IF V<1 OR V>2 THEN 4390
4420 IF V=1 THEN M(3)=Q(4):B(3)=Q(5):ELSE M(3)=Q(6):B(3)=Q(7)
4430 PRINT TAB(21)Q(8)","Q(9)UP$
4440 INPUT "  CONC INSP O2 & CO2";Q(8),Q(9)
4450 PRINT BP$DN$" PRINT VARIABLES "RN$"(Y/N)"
4460 GETKEY A$:IF A$<>"Y" AND A$<>"N" THEN 4460
4470 PRINT UP$"                             "UP$:IF A$="N" THEN4560
4480 OPEN 4,4:PRINT#4:PRINT#4,CHR$(14)"RGE CONTROL VARIABLES"CHR$(15)
4490 PRINT#4,"DATE "DA$,"TIME "LEFT$(TI$,4)
4500 PRINT#4,"NO. OF SAMPLES ="Q(0)
4510 PRINT#4,"SAMPLE FREQ.   ="Q(2)"HZ"
4520 IF V=2 THEN A$="(5*.1)":ELSE A$="(2*.1)"
4530 PRINT#4,"SENSITIVITY SETTING = "A$
4540 PRINT#4," FLOW CONVER. EQTN.  Y ="FNR4(M(3))"X  - "FNR4(B(3))
4550 PRINT#4,"INSP. O2 & CO2 CONC. ="Q(8)","Q(9):PRINT#4:CLOSE 4
4560 OPEN 2,8,2,"@0:CONT-VAR,SEQ,W"
4570 FOR X=0 TO 9:PRINT#2,Q(X):NEXT:CLOSE 2
4580 RETURN
4590 REM
4600 REM ENVIRONMENTAL VARIABLES SUBROUTINE
4610 REM
4620 OPEN 2,8,2,"0:ENVR-VAR,SEQ,R"
4630 FOR X=0 TO 3:INPUT#2,E(X):NEXT:CLOSE 2
4640 REM CHECK FOR DISK ERRORS
4650 GOSUB 7860:IF DS=62 OR DS=74 THEN 4620
4660 PRINT BP$" CHANGE ENVIRON VARIABLES "RN$"(Y/N)"
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```
4670 GETKEY A$:IF A$<>"Y" AND A$<>"N" THEN 4670
4680 PRINT UP$TAB(26)"(Y/N)"
4690 IFA $="N" AND FL(5)=1 THEN 4860
4700 PRINT TAB(21)E(0)UP$:INPUT "  AMBIENT TEMP. (K) ";E(0)
4710 PRINT TAB(21)E(1)UP$:INPUT "  BODY TEMP.     (K) ";E(1)
4720 PRINT TAB(27)E(2)UP$:INPUT "  BAROMETRIC PRES. (MMHG) ";E(2)
4730 PRINT TAB(23)E(3)UP$:INPUT "  VALVE DEAD SPACE (L)";E(3)
4740 PRINT BP$DN$" PRINT VARIABLES "RN$"(Y/N)"
4750 GETKEY A$:IF A$<>"Y" AND A$<>"N" THEN 4750
4760 PRINT UP$"                      ":IF A$="N" THEN 4840
4770 OPEN 4,4
4780 PRINT#4:PRINT#4,CHR$(14)"RGE ENVIRONMENTAL VARIABLES"CHR$(15)
4790 PRINT#4,"DATE "DA$,"TIME "LEFT$(TI$,4)
4800 PRINT#4,"AMBIENT TEMP ="E(0)"K"
4810 PRINT#4,"BODY TEMP    ="E(1)"K"
4820 PRINT#4,"BAROMETRIC PRESS. ="E(2)"MMHG"
4830 PRINT#4,"VALVE DEAD SPACE  ="E(3)"L":PRINT#4:CLOSE 4
4840 OPEN 2,8,2,"@0:ENVR-VAR,SEQ,W"
4850 FOR X=0 TO 3:PRINT#2,E(X):NEXT:CLOSE 2
4860 TA=E(0):TB=E(1):TS=273:REM AMBIENT, BODY, AND STND TEMPERATURES
4870 TX=TB-5:REM TEMP OF EXP AIR AT THE PNEUMOTACH
4880 BP=E(2):PS=760:REM BAROMETRIC AND STND PRESSURE
4890 PA=FNPW(TA):PB=FNPW(TB):REM PH20 100% SAT AT AMBIENT AND BODY TEMP
4900 PI=PA*.60:PE=FNPW(TX)*.95:REM PH20 IN INSPIRED AND EXPIRED AIR
4910 REM CONVERSION CONSTANTS
4920 K1=(TS*BP)/(TA*PS):REM CONVERT ATPD TO STPD
4930 K2=(TS*BP*(BP-PE))/(TX*PS*BP):REM CONVERT BTPS(EXP) TO STPD
4940 K3=(TS*BP)/(TX*PS):REM CONVERT BTPD(EXP) TO STPD
4950 K4=(TA*(BP-PE))/(TX*BP):REM CONVERT BTPS(EXP) TO ATPD
4960 K5=(BP-PE)/BP:REM CONVERT ATP(EXP) TO ATPD
4970 FL(5)=1:RETURN
4980 REM
4990 REM ASSEMBLY LANGUAGE SAMPLING SUBROUTINE, (1300H-1399H)
5000 REM
5010 POKE 4869,1:POKE 4870,6:POKE 4871,7:REM CHANNELS TO BE SAMPLED (CH-1)
5020 TE=(1E6/Q(2))-150:HI=FNR(TE/1400):LO=TE-HI*1400
5030 IF LO<0 THEN HI=HI-1:LO=255
5040 IF LO>256 THEN LO=255
5050 POKE 4864,LO:POKE 4865,HI:REM LO AND HI-BYTE FOR LONG DELAY
5060 POKE 4914,15:REM SHORT DELAY
5070 HI=INT(Q(0)/256):LO=Q(0)-HI*256
5080 IF LO<0 THEN HI=HI-1:LO=Q(0)-HI*256
5090 POKE 4866,LO:POKE 4867,HI:REM LO AND HI-BYTE FOR NUMBER OF SAMPLES
5100 POKE 4868,3:REM NUMBER OF CHANNELS TO BE SAMPLED
5110 RETURN
5120 REM
5130 REM HI-RES GRAPHICS SUBROUTINE
5140 REM
5150 PRINT CS$DN$" "RN$"GRAPHICS"
5160 PRINT BP$DN$" "RN$" 1 "RF$"  NORMAL SCALE (320 BY 200)"
5170 PRINT DN$" "RN$" 2 "RF$"  SQUEEZE (# OF SAMPLES BY 200)"
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5180 GETKEY A$:V=VAL(A$):IF V<1 OR V>2 THEN 5180
5190 REM SETUP SCREEN
5200 GOSUB 610:IF V=1 OR Q(0)<320 THEN XS=320:ELSE XS=Q(0)
5210 GRAPHIC 1,1:SCALE 1,XS,200:O1=.025*XS:O2=.96875*XS
5220 BOX 1,O1,0,O2,63:BOX 1,O1,68,O2,131:BOX 1,O1,136,O2,199
5230 FOR X=O1 TO O2 STEP (1.0/DT):FOR Z=0 TO 60 STEP 60
5240 FOR Y=0+Z TO 199+Z STEP 68:DRAW 1,X,Y TO X,Y+3:NEXT:NEXT:NEXT
5250 CHAR 1,2,1,"FLOW":CHAR 1,2,9,"%O2":CHAR 1,2,18,"%CO2":Y=63:W=63/256
5260 CHAR 1,33,0,"C",1:CHAR 1,34,0," OMP ",0
5270 CHAR 1,33,1,"L",1:CHAR 1,35,1,"INE ":CHAR 1,33,2,"RETURN",1
5280 REM IF DATA TO BE GRAPHED ARE FROM CAL SUBR THEN AD=N1-50
5290 IF FL(9)=1 THEN AD=N1-50:ELSE AD=0
5300 FOR Z=0 TO 2:FOR X=O1 TO O2 STEP2
5310 DRAW 1,X,Y-D%(Z,X+AD)*W:NEXT:Y=Y+68:NEXT
5320 REM IF DATA TO BE GRAPHED ARE COMPENSATED FOR THE LAG TIME AND
5330 REM RESP OF THE ANALYZERS USING NOGUCHI'S METHOD THEN GOTO 5450
5340 IF FL(4)=1 THEN 5470
5350 GETKEY A$
5360 IF A$=CHR$(13) THEN PRINT CS$:GRAPHIC 0:FL(4)=0:FL(9)=0:RETURN
5370 IF A$="C" THEN 5440
5380 Y=63:W=63/256:DRAW 1,O1,Y+CA(1)*W TO O2,Y+CA(1)*W
5390 FOR Z=3 TO NB*4-1 STEP4:IF C(Z)<XS THEN DRAW 1,C(Z),0 TO C(Z),199
5400 NEXT:FOR Z=4 TO NB*4 STEP4:IF C(Z)<XS THEN DRAW 1,C(Z),0 TO C(Z),199
5410 NEXT:IF FL(9)=0 THEN 5430
5420 DRAW 1,O1,131-MN*WTOO2,131-MN*W:DRAW 1,O1,199-MX*WTOO2,199-MX*W
5430 GOTO 5350
5440 Y=131:W=63/256:FOR Z=1TO2:FOR X=O1 TO O2 STEP2
5450 DRAW 0,X,Y-D%(Z,X+AD)*W:DRAW 1,X,Y-D%(Z,X+LT(Z)+AD)*W:NEXT
5460 Y=Y+68:NEXT:GOTO 5350
5470 GETKEY A$
5480 IF A$=CHR$(13) THEN PRINT CS$:GRAPHIC 0:FL(4)=0:FL(9)=0:RETURN
5490 IF A$="C" THEN 5540
5500 Y=63:W=63/256:DRAW 1,O1,Y+CA(1)*W TO O2,Y+CA(1)*W
5510 FOR Z=3 TO 11 STEP4:IF C(Z)<XS THEN DRAW 1,C(Z),0 TO C(Z),199:NEXT
5520 FOR Z=4 TO 12 STEP 4:IF C(Z)<XS THEN DRAW 1,C(Z),0 TO C(Z),199:NEXT
5530 GOTO 5470
5540 Y=131:W=63/256:FOR Z=1 TO 2:FOR X=O1 TO O2 STEP2
5550 DRAW 0,X,Y-D%(Z,X)*W:DRAW 1,X,Y-E%(Z+1,X)*W:NEXT:Y=Y+68:NEXT
5560 GOTO 5470
5570 REM
5580 REM RGE CALIBRATION SUBROUTINE
5590 REM
5600 L$="CALIBRATION SUBROUTINE":GOSUB 4150
5610 OPEN 2,8,2,"0:CAL-CONST,SEQ,R"
5620 REM CHECK FOR DISK ERRORS
5630 GOSUB 7860:IF DS=62 OR DS=74 THEN 910
5640 FOR X=1 TO 10:INPUT#2,CA(X):NEXT
5650 INPUT#2,GA(1),GA(2),B(1),B(2),M(1),M(2):CLOSE 2
5660 PRINT BP$" "RN$" 1 "RF$"  ENTIRE CALIBRATION SUBROUTINE"
5670 PRINT DN$" "RN$" 2 "RF$"  PNEUMOTACH CALIBRATION"
5680 PRINT DN$" "RN$" 3 "RF$"  O2 AND CO2 ANALYZER CALIBRATION"
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5690 PRINT DN$" "RN$" 4 "RF$"  CALCULATE ANALYZER LAG TIME"
5700 PRINT DN$" "RN$" 5 "RF$"  DISPLAY CALIBRATION CONSTANTS"
5710 GETKEY A$:V=VAL(A$):IF V<1 OR V>5 GOTO 5710:ELSE GOSUB 610
5720 ON V GOTO 5730:ON V-1 GOSUB 5770,6190,6530:GOTO 7260
5730 GOSUB 5770:GOSUB 6190:GOSUB 6530:GOTO 7260
5740 REM
5750 REM CALCULATE PNEMOTACH ZERO OFFSET
5760 REM
5770 PRINT DN$" A) PNEUMOTACH"
5780 PRINT TAB(3)DN$"1.AFTER SETTING THE FLOW RATE TO"
5790 PRINT TAB(5)"0 L/MIN TYPE "RN$"RETURN"
5800 GET A$:IF A$<>CHR$(13) THEN 5800:ELSE GOSUB 610
5810 PRINT TAB(5)UP$"0 L/MIN TYPE RETURN":FAST:FOR X=1 TO 50:POKE CH(1),0
5820 L(X)=PEEK (CH(1)):NEXT:C=0:FOR X=1 TO 49:C=C+ABS(L(X+1)-L(X))
5830 IF C>10 THEN 5810
5840 CA(1)=0:FOR X=1 TO 50:CA(1)=CA(1)+L(X):NEXT:CA(1)=-FNR2(CA(1)/(X-1))
5850 PRINT TAB(12)"           "UP$:PRINT TAB(5)"CA(1) ="FNR2(CA(1)):SLOW
5860 PRINT BP$TAB(5)"CONTINUE "RN$"(Y/N)"
5870 GETKEY A$:IF A$<>"Y" AND A$<>"N" THEN 5870
5880 PRINT UP$TAB(5)"              "
5890 IF A$="N" THEN PRINT DN$DN$DN$:GOTO 6140
5900 REM
5910 REM COMPARE CALCULATED VOLUME WITH ACTUAL
5920 REM VOLUME (1 LITER)
5930 REM
5940 PRINT BP$TAB(3)"2.TYPE "RN$"RETURN"RF$" BEFORE PUSHING"
5950 PRINT TAB(5)"A KNOWN VOL OF AIR THROUGH"
5960 PRINT TAB(5)"THE PNEUMOTACH"
5970 GET A$:IF A$<>CHR$(13) THEN 5970
5980 GOSUB 610:PRINT UP$UP$UP$TAB(3)"2.TYPE RETURN BEFORE PUSHING"DN$DN$
5990 FAST
6000 SLEEP 3:GOSUB 600
6010 Y=0:T1=TI:FOR X=1 TO 500:POKE CH(1),0:D%(0,X)=PEEK (CH(1)):NEXT
6020 T2=TI-T1:DT=T2/(60*500)
6030 GOSUB 600:Z=1:C1=0:C2=0:FOR X=1 TO 500:ON Z GOTO 6040,6060
6040 IF ABS(D%(0,X)+CA(1))>10 THEN C1=X:Z=2
6050 GOTO 6070
6060 IF ABS(D%(0,X)+CA(1))<5 THEN C2=X:X=500
6070 NEXT:IF C2=0 THEN SLOW:ELSE 6090
6080 PRINT "   ***YOU TOOK TO LONG TRY AGAIN***"UP$UP$UP$UP$:GOTO5940
6090 CA(2)=0:FOR X=C1+1 TO C2-1:CA(2)=FNF(D%(0,X))+CA(2):NEXT
6100 CA(2)=((CA(2)+(FNF(D%(0,C1))+FNF(D%(0,C2)))/2)*DT)*1E3:SLOW
6110 PRINT TAB(15)"         "UP$
6120 PRINT "     CALC VOL ="INT(CA(2))"ML               "
6130 PRINT "                                     "UP$
6140 PRINT BP$TAB(5)"REPEAT PART A "RN$"(Y/N)"RF$
6150 GETKEY A$
6160 IF A$<>"Y" AND A$<>"N" THEN 6150
6170 PRINT UP$TAB(5)"                    "
6180 IF A$="N" THEN RETURN:ELSE FOR X=1TO12:PRINT UP$;:NEXT:GOTO 5770
6190 PRINT DN$" B) O2 AND CO2 GAS ANALYZERS"
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6200 PRINT DN$"   1.BEGIN SAMPLING DRY ROOM AIR THEN"
6210 PRINT BP$TAB(5)"TYPE "RN$"RETURN"
6220 GET A$:IF A$<>CHR$(13) THEN 6220:ELSE GOSUB 610
6230 PRINT UP$TAB(10)"RETURN"
6240 FOR X=1 TO 50:POKE CH(2),0:L(X)=PEEK (CH(2)):NEXT
6250 C=0:FOR X=1 TO 50:C=C+ABS(L(X+1)-L(X)):IF C>10 THEN 6240
6260 C=0:FOR X=1 TO 50:CA(3)=CA(3)+L(X):NEXT:CA(3)=CA(3)/(X-1)
6270 FOR X=1 TO 50:POKE CH(3),0:L(X)=PEEK (CH(3)):NEXT
6280 C=0:FOR X=1 TO 50:C=C+ABS(L(X+1)-L(X)):IF C>10 THEN 6270
6290 C=0:FOR X=1 TO 50:CA(5)=CA(5)+L(X):NEXT:CA(5)=CA(5)/(X-1)
6300 PRINT BP$DN$TAB(32)"14.8"UP$
6310 INPUT "   2.ENTER %O2 IN THE CAL. GAS";GA(1)
6320 GA(1)=GA(1)/100
6330 PRINT TAB(5)"A)BEGIN SAMPLING CALIBRATION GAS"
6340 PRINT BP$TAB(7)"THEN TYPE "RN$"RETURN"
6350 GET A$:IF A$<>CHR$(13) THEN 6350
6360 GOSUB 610:PRINT UP$TAB(17)"RETURN"
6370 FOR X=1 TO 50:POKE CH(2),0:L(X)= PEEK (CH(2)):NEXT
6380 C=0:FOR X=1 TO 50:C=C+ABS(L(X+1)-L(X)):IF C>10 THEN 6360
6390 CA(4)=0:FOR X=1 TO 50:CA(4)=CA(4)+L(X):NEXT:CA(4)=CA(4)/(X-1)
6400 M(1)=((Q(8))-GA(1))/(CA(3)-CA(4)):B(1)=Q(8)-M(1)*CA(3)
6410 PRINT BP$DN$TAB(33)"4.7"UP$
6420 INPUT "   3.ENTER %CO2 IN THE CAL. GAS";GA(2)
6430 GA(2)=GA(2)/100
6440 PRINT TAB(5)"A)BEGIN SAMPLING CALIBRATION GAS"
6450 PRINT BP$TAB(7)"THEN TYPE "RN$"RETURN"
6460 GET A$:IF A$<>CHR$(13) THEN 6460
6470 GOSUB 610:PRINT UP$TAB(17)"RETURN"
6480 FOR X=1 TO 50:POKE CH(3),0:L(X)=PEEK (CH(3)):NEXT
6490 C=0:FOR X=1 TO 50:C=C+ABS(L(X+1)-L(X)):IF C>10 THEN 6480
6500 CA(6)=0:FOR X=1 TO 50:CA(6)=CA(6)+L(X):NEXT:CA(6)=CA(6)/(X-1)
6510 M(2)=GA(2)/(CA(6)-CA(5)):B(2)=GA(2)-M(2)*CA(6):RETURN
6520 REM
6530 REM CALCULATE ANALYZER TRANSPORT DELAY AND RESPONSE
6540 REM
6550 PRINT DN$" C) ANALYZER LAG TIME AND RESPONSE"DN$
6560 PRINT BP$TAB(25)FNR4(CA(7))UP$
6570 INPUT "      O2 ANALYZER DELAY =";CA(7)
6580 PRINT BP$TAB(28)FNR4(CA(9))UP$
6590 INPUT "      O2 ANALYZER RESPONSE =";CA(9)
6600 PRINT BP$TAB(26)FNR4(CA(8))UP$
6610 INPUT "      CO2 ANALYZER DELAY =";CA(8)
6620 PRINT BP$TAB(29)FNR4(CA(10))UP$
6630 INPUT "      CO2 ANALYZER RESPONSE =";CA(10)
6640 PRINT BP$DN$TAB(5)"RECALCLUATE LT & RESP "RN$"(Y/N)"
6650 GETKEY A$
6660 IF A$<>"Y" AND A$<>"N" THEN 6650:ELSE PRINT UP$TAB(27)"(Y/N)"
6670 IF A$="N" THEN 7260:ELSE 6690
6680 PRINT UP$TAB(3)"  ***YOU TOOK TO LONG TRY AGAIN***  "UP$UP$
6690 PRINT UP$TAB(3)"1.BEFORE MAKING THE MEASUREMENT"
6700 PRINT BP$TAB(5)"TYPE "RN$"RETURN"RF$
```

```
6710 GET A$:IF A$<>CHR$(13) THEN 6710
6720 GOSUB 610:PRINT UP$TAB(10)"RETURN"
6730 PRINT TAB(5)"                                              "
6740 TE(1)=Q(0):TE(2)=Q(2):Q(0)=1250:Q(2)=250:GOSUB 5010
6750 SLEEP3:GOSUB 600:T1=TI:SYS4886:T2=TI-T1:GOSUB 600
6760 FAST
6770 DT=T2/(Q(0)*60):ZE(0)=0:ZE(1)=0:ZE(2)=0:MN=0:MX=0
6780 FOR N=0 TO 2:ZE(N)=0:FOR X=0 TO 49:ZE(N)=ZE(N)+D%(N,X):NEXT
6790 ZE(N)=ZE(N)/50:NEXT:FOR N=0 TO 2:D%(N,Q(0))=255:NEXT
6800 D%(1,Q(0))=0:N1=0:A1=ZE(0)+5
6810 DO UNTIL D%(0,X)>A1:X=X+1:LOOP
6820 IF X=Q(0) THEN SLOW:GOTO 6680
6830 N1=X:GOSUB 610
6840 N2=0:A1=ZE(1)-4:X=X+50:DO UNTIL D%(1,X)<A1:X=X+1:LOOP
6850 IF X=Q(0) THEN SLOW:GOTO 6680
6860 N2=X:GOSUB 610
6870 N3=0:A1=ZE(2)+4:X=X-50:DO UNTIL D%(2,X)>A1:X=X+1:LOOP
6880 IF X=Q(0) THEN SLOW:GOTO 6680
6890 N3=X:GOSUB 610
6900 FOR X=N3+201 TO N3+250:MN=MN+D%(1,X):MX=MX+D%(2,X):NEXT
6910 MN=MN/50:MX=MX/50
6920 N4=0:Y=ZE(1)-.63*(ZE(1)-MN):X=N2:DO UNTIL D%(1,X)<Y:X=X+1:LOOP:N4=X
6930 DO UNTIL D%(1,X)<Y:X=X+1:LOOP:N4=X
6940 IF N4>N2+200 THEN SLOW:GOTO 6680
6950 GOSUB 610
6960 N5=0:Y=ZE(2)+.63*(MX-ZE(2)):X=N3:DO UNTIL D%(2,X)>Y:X=X+1:LOOP:N5=X
6970 IF N5>N3+200 THEN SLOW:GOTO 6680
6980 GOSUB 610
6990 CA(7)=(N2-N1)*DT:CA(8)=(N3-N1)*DT
7000 CA(9)=(N4-N2)*DT:CA(10)=(N5-N3)*DT
7010 Q(0)=TE(1):Q(2)=TE(2)
7020 SLOW
7030 PRINT TAB(6)"O2 ANALYZER DELAY ="FNR4(CA(7))
7040 PRINT TAB(6)"O2 ANALYZER RESPONSE ="FNR4(CA(9))
7050 PRINT TAB(6)"CO2 ANALYZER DELAY ="FNR4(CA(8))
7060 PRINT TAB(6)"CO2 ANALYZER RESPONSE ="FNR4(CA(10))
7070 PRINT BP$DN$TAB(6)"GRAPH "RN$"(Y/N)"
7080 GETKEY A$
7090 IF A$<>"Y" AND A$<>"N" THEN 7080:ELSE PRINT UP$TAB(12)"(Y/N)"
7100 IF A$="Y" THEN 7160:ELSE Q(0)=TE(1):Q(2)=TE(2)
7110 PRINT BP$UP$TAB(5)"REPEAT PART 1. "RN$"(Y/N)"
7120 GETKEY A$
7130 IF A$<>"Y" AND A$<>"N" THEN 7120
7140 PRINT UP$"                                "
7150 IF A$="N" THEN 7260:ELSE FORX=1TO8:PRINT UP$;:NEXT:GOTO 6690
7160 TE=50-N1:C(3)=N1+TE:C(4)=N2+TE:C(7)=N3+TE:C(8)=N4+TE
7170 C(11)=N5+TE:C(12)=N5+TE
7180 LT(1)=(CA(7)+CA(9))/DT:LT(2)=(CA(8)+CA(10))/DT
7190 FL(9)=1:GOSUB 5150:Q(0)=TE(1):Q(2)=TE(2):GOTO 6550
7200 REM
7210 REM PRINT CALIBRATION CONSTANTS
```

```
7220 REM
7230 FL(1)=1:OPEN 2,8,2,"0:CAL-CONST,SEQ,R"
7240 FOR X=1 TO 10:INPUT#2,CA(X):NEXT
7250 INPUT#2,GA(1),GA(2),B(1),B(2),M(1),M(2):CLOSE 2
7260 SLOW:L$="CALIBRATION CONSTANTS AND EQUATIONS":GOSUB 4150
7270 PRINT " CA1 (FLOW ZERO)="CA(1)
7280 PRINT " CA2 (VOL CHECK)="INT(CA(2))"ML"
7290 PRINT " CA3 (X1 %O2)="INT(CA(3));
7300 PRINT " CA4 (X2 %O2)="INT(CA(4))
7310 PRINT " CA5 (X1 %CO2)="INT(CA(5));
7320 PRINT " CA6 (X2 %CO2)="INT(CA(6))
7330 PRINT " CA7 (LT O2)="FNR4(CA(7))" SEC"
7340 PRINT " CA8 (LT CO2)="FNR4(CA(8))" SEC"
7350 PRINT " CA9 (TC O2)="FNR4(CA(9))" SEC"
7360 PRINT " CA10 (TC CO2)="FNR4(CA(10))" SEC"
7370 PRINT " GA1 (CAL GAS %O2)="GA(1)
7380 PRINT " GA2 (CAL GAS %CO2)="GA(2)
7390 PRINT " CONV EQTN %O2="FNR6(M(1))"X + "FNR4(B(1))
7400 PRINT " CONV EQTN %CO2="FNR6(M(2))"X + "FNR4(B(2))
7410 PRINT BP$DN$" PRINT CONSTANTS "RN$"(Y/N)"
7420 GETKEY A$:IF A$<>"Y" AND A$<>"N" THEN 7420
7430 IF A$="N" THEN 7650
7440 PRINT UP$" PRINT CONSTANTS (Y/N)"
7450 REM
7460 REM PRINT HARD-COPY OF CALIBRATION CONSTANTS
7470 REM
7480 OPEN 4,4:PRINT#4:PRINT#4,CHR$(14)"RGE CALIBRATION CONSTANTS"CHR$(15)
7490 PRINT#4,"DATE "DA$,"TIME "LEFT$(TI$,4)
7500 PRINT#4,"CA1 (FLOW ZERO)="CA(1)
7510 PRINT#4,"CA2 (VOL CHECK)="INT(CA(2))"ML"
7520 PRINT#4,"CA3 (X1 O2)="INT(CA(3));
7530 PRINT#4,"    CA4 (X2 O2)="INT(CA(4))
7540 PRINT#4,"CA5 (X1 CO2)="INT(CA(5));
7550 PRINT#4,"    CA6 (X2 CO2)="INT(CA(6))
7560 PRINT#4,"CA7 (LT O2)="FNR4(CA(7))"SEC";
7570 PRINT#4,"     CA9 (TC O2)="FNR4(CA(9))"SEC"
7580 PRINT#4,"CA8 (LT CO2)="FNR4(CA(8))"SEC";
7590 PRINT#4,"    CA10 (TC CO2)="FNR4(CA(10))"SEC"
7600 PRINT#4,"GA1 (CAL GAS %O2)="GA(1)
7610 PRINT#4,"GA2 (CAL GAS %CO2)="GA(2)
7620 PRINT#4,"O2 CONV EQTN %O2="FNR6(M(1))"X + "FNR4(B(1))
7630 PRINT#4,"CO2 CONV EQTN %CO2="FNR6(M(2))"X + "FNR4(B(2))
7640 PRINT#4:CLOSE 4
7650 PRINT BP$UP$" "RN$" 1 "RF$"  SAVE CAL. CONST. ON DISK"
7660 PRINT DN$" "RN$" 2 "RF$"  RETURN TO OPENING MENU"
7670 PRINT DN$" "RN$" 3 "RF$"  BEGIN SAMPLING ROUTINE"
7680 GETKEY A$
7690 V=VAL(A$):IF V<1 OR V>3 THEN 7680
7700 GOSUB 610:ON V GOTO 7750,7710,7710,7710
7710 PRINT CS$:ON V-1 GOTO 910,1410,1590
7720 REM
```

```
7730 REM STORE CALIBRATION CONSTANTS ON DISK
7740 REM
7750 PRINT UP$UP$UP$UP$UP$"  1 "
7760 OPEN 2,8,2,"@0:CAL-CONST,SEQ,W"
7770 FOR X=1 TO 10:PRINT#2,CA(X):NEXT
7780 PRINT#2,GA(1);R$;GA(2);R$;B(1);R$;B(2);R$;M(1);R$;M(2)
7790 CLOSE 2:PRINT BP$;:GOTO 7680
7800 REM
7810 REM ERROR TRAPPING
7820 REM
7830 GRAPHIC 0:SLOW:PRINT RN$ERR$(ER);EL
7840 PLAY "V1O3T8U8X0HDQDO4WF":STOP
7850 REM
7860 REM DISK ERROR CHECK SUBROUTINE
7870 REM
7880 GRAPHIC 0:SLOW
7890 F1$=RN$+" DISK ERROR"+RF$+": DISK NOT FOUND, TYPE "+RN$+"C"+RF$
7900 F2$=RN$+" DISK ERROR"+RF$+": FILE NOT FOUND, TYPE "+RN$+"C"+RF$
7910 IF DS=74 THEN PRINT DN$BP$F1$:GOTO 7930
7920 IF DS=62 THEN PRINT DN$BP$F2$:ELSE RETURN
7930 PRINT TAB(13)"TO CONTINUE"UP$
7940 GETKEY A$:IF A$<>"C" THEN 7940:ELSE GOSUB 610
7950 PRINT UP$"                                   "
7960 PRINT TAB(13)"           "UP$UP$
7970 RETURN

READY.
```

ASSEMBLY LANGUAGE SAMPLING PROGRAM

```
. 01300  00        BRK          ;Lo-byte delay loop
. 01301  00        BRK          ;Hi-byte delay loop
. 01302  00        BRK          ;Lo-byte number of samples
. 01303  00        BRK          ;Hi-byte number of samples
. 01304  00        BRK          ;Number of channels to be sampled
. 01305  00        BRK          ;The next 16 bytes are used to store
. 01306  00        BRK          ; the numbers (0-15) of the ADC
. 01307  00        BRK          ; channels which will be sampled.
. 01308  00        BRK          ; The BASIC array D%(x,y) which is
. 01309  00        BRK          ; used for data storage must be
. 0130A  00        BRK          ; dimensioned (in the BASIC program)
. 0130B  00        BRK          ; so that x = number of channels to
. 0130C  00        BRK          ; be sampled - 1. D%(x,y) must also
. 0130D  00        BRK          ; be the first array dimensioned in
. 0130E  00        BRK          ; the BASIC program.
. 0130F  00        BRK          ;
. 01310  00        BRK          ;
. 01311  00        BRK          ;
. 01312  00        BRK          ;
. 01313  00        BRK          ;
. 01314  00        BRK          ;
. 01315  EA        NOP          ;
. 01316  AD 32 00  LDA $0032    ;Copy address of BASIC array D%(x,y)
. 01319  8D FC 00  STA $00FC    ; from $31 and $32 (lo and hi-bytes of
. 0131C  AD 31 00  LDA $0031    ; pointer:  start of BASIC arrays) to
. 0131F  18        CLC          ; $FB and $FC ($FB and $FC will be
. 01320  69 0A     ADC #$0A     ; used with a bank switching kernal
. 01322  8D FB 00  STA $00FB    ; subroutine). The array header is 10
. 01325  90 03     BCC $132A    ; bytes long.
. 01327  EE FC 00  INC $00FC    ;
. 0132A  A9 FB     LDA #$FB     ;Setup indirect vector ($2B9) for
. 0132C  8D B9 02  STA $02B9    ; kernal subroutine.
. 0132F  A0 00     LDY #$00     ;Clear Y reg
. 01331  A2 10     LDX #$10     ;Load X reg with short delay count
. 01333  B9 05 13  LDA $1305,Y  ;Load accum with number of ADC
. 01336  8D 3F 13  STA $133F    ; channels to be sampled.
. 01339  8D 45 13  STA $1345    ;
. 0133C  A9 00     LDA #$00     ;Clear accum
. 0133E  8D 02 DF  STA $DF02    ;Store 0 to start conversion
. 01341  CA        DEX          ;Short delay, ADC settling time
. 01342  D0 FD     BNE $1341    ;
. 01344  AD 02 DF  LDA $DF02    ;Load accum with sampled data
. 01347  8C FA 00  STY $00FA    ;Store Y reg count
. 0134A  A2 01     LDX #$01     ;X reg = bank
. 0134C  A0 00     LDY #$00     ;Y reg = index
. 0134E  20 77 FF  JSR $FF77    ;Write data to array D%(x,y)
. 01351  A9 00     LDA #$00     ; (both lo and hi-bytes) using
. 01353  A2 01     LDX #$01     ; kernal jump table.
. 01355  C8        INY          ;
```

```
. 01356  20 77 FF JSR $FF77     ;
. 01359  18       CLC           ;
. 0135A  AD FB 00 LDA $00FB     ;Increment array address by 2
. 0135D  69 02    ADC #$02      ;
. 0135F  8D FB 00 STA $00FB     ;
. 01362  90 03    BCC $1367     ;
. 01364  EE FC 00 INC $00FC     ;
. 01367  AC FA 00 LDY $00FA     ;Return count to reg Y, increment
. 0136A  C8       INY           ; reg Y, and compare with number
. 0136B  CC 04 13 CPY $1304     ; of channels to be sampled. If
. 0136E  F0 03    BEQ $1373     ; all channels have not been
. 01370  4C 31 13 JMP $1331     ; sampled jump to $1331.
. 01373  AD 02 13 LDA $1302     ;Decrement the number of samples
. 01376  D0 03    BNE $137B     ; left to be taken.
. 01378  CE 03 13 DEC $1303     ;
. 0137B  CE 02 13 DEC $1302     ;If samples are left to be taken
. 0137E  A9 00    LDA #$00      ; branch to $138A. If no samples
. 01380  CD 03 13 CMP $1303     ; are left to be taken, branch to
. 01383  D0 05    BNE $138A     ; $1399.
. 01385  CD 02 13 CMP $1302     ;
. 01388  F0 0F    BEQ $1399     ;
. 0138A  AE 00 13 LDX $1300     ;Long delay
. 0138D  AC 01 13 LDY $1301     ;
. 01390  CA       DEX           ;
. 01391  D0 FD    BNE $1390     ;
. 01393  88       DEY           ;
. 01394  D0 FA    BNE $1390     ;
. 01396  4C 2F 13 JMP $132F     ;
. 01399  60       RTS           ;Return to BASIC program.
```