INTERN EXPERIENCE AT

THE HONEYWELL TEST INSTRUMENT DIVISION

AN INTERNSHIP REPORT

by

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Submitted to the College of Engineering
of Texas A&M University in partial fulfillment
of the requirements for the degree of

DOCTOR OF ENGINEERING

December 1977

Major Subject: Bioengineering

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December 1977

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to..

..Dr. Arthur M. Sherwood for acting as my committee chairman and for guiding me through the program.

..Dr. William A. Hyman for accepting the responsibility of serving as the co-chairman at a very late date.

..Dr. Charles A. Rodenberger for his tremendous help in securing an internship position.

..Dr. Make McDermott for being so helpful and understanding as the head of the VA project I worked for.

..Ronald E. West for all his effort in making my internship period useful and worthwhile.

..Charles S. Clark and Arun P. Sheth for all their help and assistance at and outside work during my stay in Denver.

..Mary H. Fenstemaker for putting up with my endless typing needs.

..Barbara McCulloch for editing and typing this report.

TO MY FATHER

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CHAPTER I

INTRODUCTION

This report documents the industrial experience accrued by the author during a twelve month Doctor of Engineering internship served with Honeywell. The internship was served at the Test Instrument Division, Denver, Colorado as a Biomedical Applications Engineer between June 15, 1976 and June 30, 1977.

This report contains details of the projects that were assigned during the period and the end results that were achieved. It outlines the activities which were non-technical in nature and which allowed interactions with various individuals and groups and gave exposure to some of the managerial activities within the division. It also contains an overview of significant observations that were made during the internship.

Objectives of the Internship

The industrial internship is an important segment of the Doctor of Engineering degree requirements. The objectives of the internship are:

1. To enable the student to demonstrate his ability to apply his knowledge and technical training by making an identifiable contribution in an area of practical concern to the organization or industry in which the internship is served.
2. To enable the student to function in a non-academic environment in a position where he will become aware of the organizational approach to problems in addition to traditional

engineering design or analysis. These may include, but are not limited to, problems of management, labor relations, public relations, environmental protection or economics.

Honeywell and Its Test Instrument Division

The internship was secured through interviews with Honeywell's Corporate Personnel and Training Department. Honeywell is a major international automation company with sales and revenues exceeding $2.4 billion in 1976. It is organized into two separate groups, the Information Systems Group, responsible for sales and servicing of a wide range of computers, and the Control Systems Group, involved in sales of a diverse group of industrial, commercial and residential control gear. An organization chart for the company appears in Figure 1.

The Test Instrument Division (TID) of the Control Systems Group is headquartered in Denver, Colorado and is a leading manufacturer of instruments and systems for the recording, display and analysis of a wide variety of test and monitoring data. The division also offers equipment maintenance services on a contract or demand basis to medical, manufacturing and government customers. The division employs approximately 1,000 persons engaged in engineering, marketing, sales, manufacturing and service. The organization chart for this division appears in Figure 2.

There are four product design groups in the division with the heads of the first three reporting to the Chief Engineer: (a) Tape Recorders, (b) Oscillographs, (c) Medical, and (d) Government Programs. The Advanced Product Planning Group is responsible for

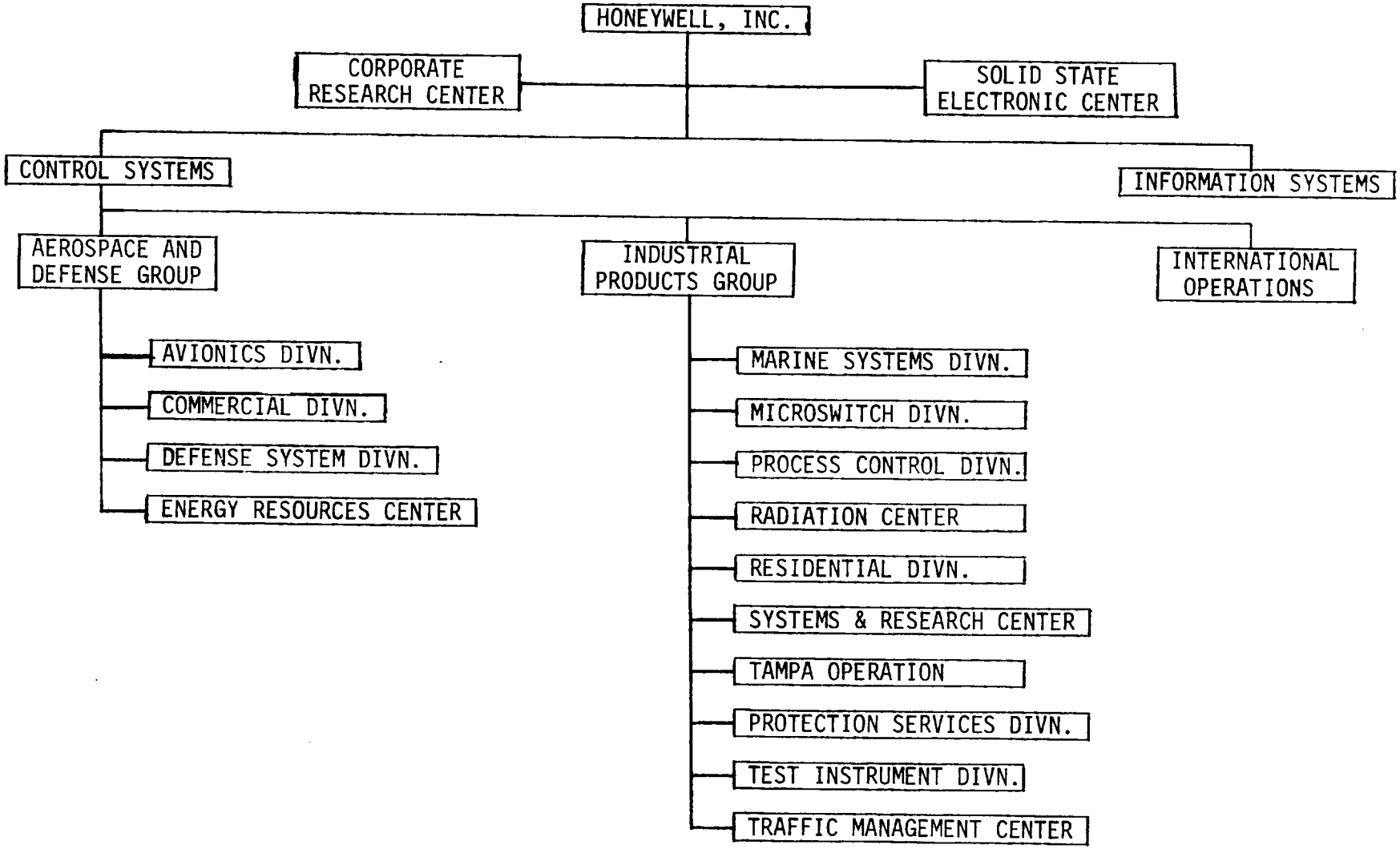


Figure 1. Honeywell Organization Chart

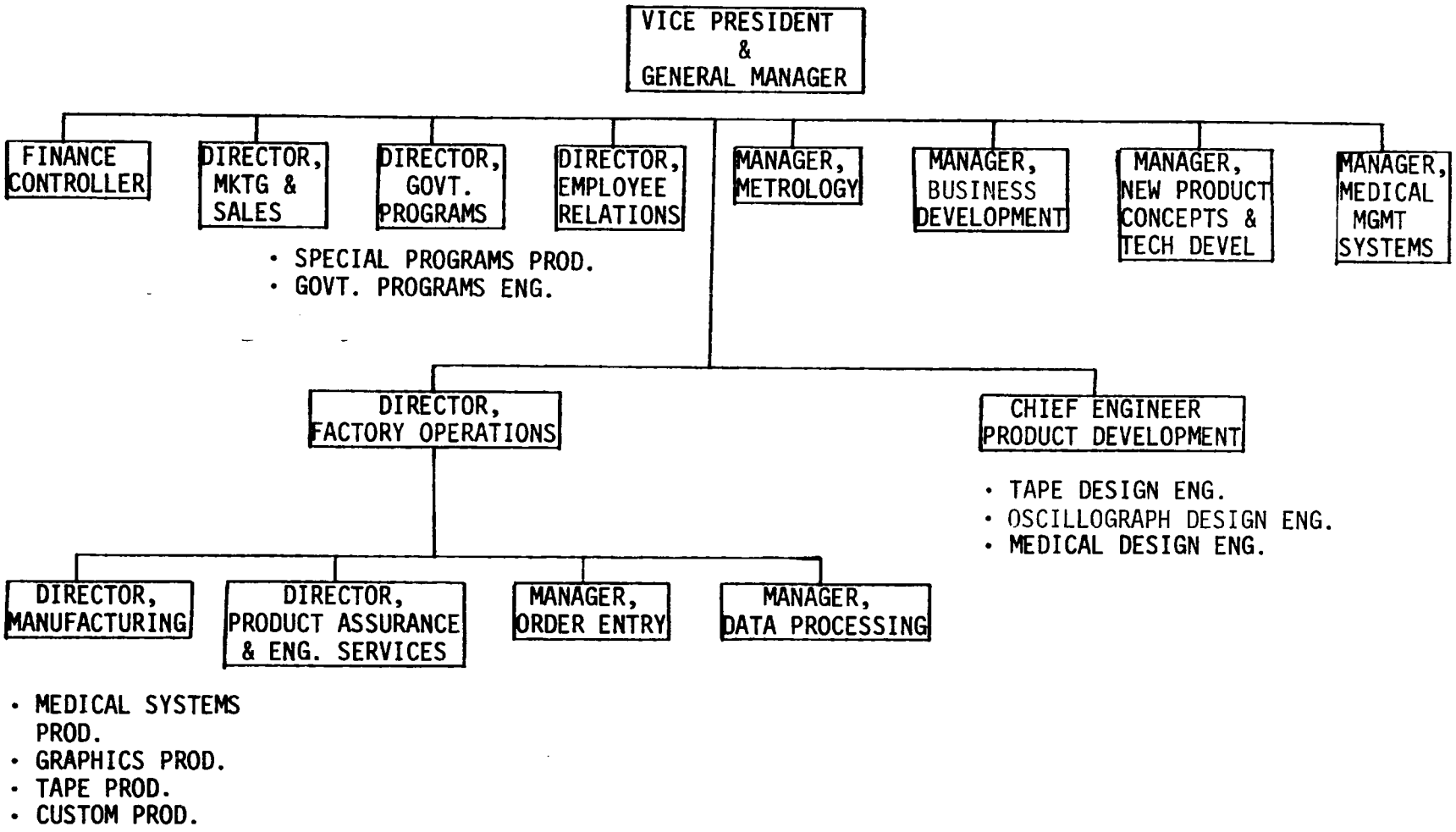


Figure 2. Test Instrument Division Organization Chart

identifying new product possibilities and its manager reports directly to the divisional General Manager.

The division manufactures tape recorders, oscillographs, signal analyzers, medical instruments and allied products. A list of the division's product offerings appears in Figure 3. It also has a Metrology Group which services and maintains medical instruments in hospitals and clinics. This is done on a contractual basis and covers equipment made by Honeywell and other manufacturers.

The factory production staff are organized into five areas: (a) tape recorders, (b) oscillograph, (c) medical, (d) custom, and (e) special programs (government contracts). A highly skilled Model Shop completes the division's production capability.

I. Visicorder Oscillographs
   - fiber-optic cathode ray tube type
   - miniature galvanometer type

II. Magnetic Tape Recorders
   - medium and wideband portable systems
   - wideband laboratory system

III. Accudata Signal Conditioning Units

IV. Signal Analyzers
   - correlation and probability analyzer
   - fourier transform analyzer

V. Industrial Systems
   - dye-casting and welding testing system
   - data transmission recording system

VI. Medical Data Acquisition Systems
   - esophageal motility and echo/phono cardiology systems

VII. MEDDARS System

VIII. ACS-1000 White Cell Differential Analyzer

Figure 3. Test Instrument Division Product Offerings

CHAPTER II

INTERNSHIP POSITION

The internship position was that of a Biomedical Applications Engineer in the Medical Engineering Group. This group consists of 15 hardware and software design engineers and 6 technicians. It is involved in designing medical data monitoring systems and instruments. Their most recent design effort resulted in a sophisticated medical display, analysis and recording system which is being marketed under the name of MEDDARS. This modular clinical equipment can be built up to a system which, in a single framework, contains signal conditioning, visual display, graphic recording, data storage and microcomputer based data analysis capabilities that can be used in a number of medical applications. The manager for the Medical Engineering Group, Ronald E. West was the internship supervisor. He reports to the Chief Engineer of the plant, J. Baring who in turn reports to the divisional Vice President, C. W. Johnson.

The assigned tasks during the internship required determining how certain customer requirements identified by the marketing or sales staff could be best satisfied using divisional and company products, know-how and resources. The requirements ranged from providing additional capabilities for existing products to satisfying needs that could not be met by any existing product.

It required (a) conducting surveys of current literature and opinions of the user community; (b) studying the operations of existing divisional and company products; (c) designing custom products and prototype versions of future standard products; (d) estimating material

and labor costs for particular projects and sales order proposals; and (e) defining complete requirements for possible future products and software application programs.

These efforts resulted in finished hardware which is being used by a customer, prototype hardware to be used as an option to a standard product, sales proposals which included both a preliminary design and a price quote sent to the customers, and functional specifications for a complete medical data acquisition and analysis system for review and possible implementation into a product. The internship position was unique in that it allowed extensive opportunity to observe closely and participate in determining specific medical market needs. It also required designing products according to existing divisional practices and guidelines. The position can be best described as that of a medical marketing applications engineer. During the internship period there was also ample opportunity to attend several top management meetings, customer conferences, and presentations by in house and outside persons. There were also opportunities to attend customer training courses on existing divisional products.

Proper functioning as the Biomedical Applications Engineer required interactions within the plant with the (a) design engineers and technicians in Medical Engineering to better understand the working of the MEDDARS system, to obtain their views on how options could be added to it and to get a prototype unit built and tested; (b) engineers with other design groups to acquaint them with the working of a medical instrument; (c) production engineers, production supervisors and drafting staff in Medical and Custom Production and the Model Shop

to get custom units built and documented; (d) marketing and sales groups to better understand their views of customer needs; (e) accounting staff to get the various sales proposals and engineering project management plans priced; (f) purchasing department to arrange for outside components purchase; and (g) field service technician to advise him on how to install a custom built interface unit.

Outside the plant, there were necessary interactions with (a) a health care consultant who was responsible for the study of market demands for certain medical products; (b) customers and medical product users to access their needs; (c) manufacturers and vendors to determine whether they could supply certain required components; and (d) engineers and marketing personnel from other Honeywell divisions to see whether they had any technology that could be useful in developing new medical products.

Several discussions were held during the year with the divisional International Marketing Group in view of probably future employment with Honeywell in its Indian subsidiary.

CHAPTER III

DETAILS OF ASSIGNED PROJECTS AND RESULTS ACHIEVED

This section describes, in some detail, the various tasks that were assigned to me during the internship period and the end results that were achieved. The sequence in which they appear does not reflect the time of their occurrence.

Pulmonary Function Laboratory System

A major portion of effort during the internship was devoted to an in-depth study of instruments and testing procedures used in pulmonary function testing laboratories. TID has, till now, catered primarily to the cardiology market. This study was to help explore a new medical application area. With favorable marketing and technical survey reports, the study could lead to the development of a new product.

It was anticipated that the study would result in a functional specification of a data acquisition, recording and analysis system which would: (a) be clinical in nature, as opposed to a system useful for research purposes only; (b) meet user approval; and (c) be significantly different from other commercially available systems in terms of cost and capabilities.

In order to arrive at a system definition, the following tasks were performed:

1. Engineering Project Management Plan: An engineering project management plan was prepared which included estimates of labor and material requirements and date of completion of the project.

2. Literature Survey: The literature survey included a comprehensive study of specific methodologies employed and parameters measured today in pulmonary function testing laboratories, and an in-depth look at instruments and systems presently used for carrying out these tests. It also included identifying possible outside contacts helpful in developing a system that would have wide user acceptance. It required determining whether the system must or should meet any performance standards set up by federal or state regulatory agencies or medical associations. Emphasis was placed, during this phase, on studying standard clinical practices applicable today and anticipated in the near future.
3. Specification Outline: This task included defining and outlining specific areas and questions that need to be addressed in the functional specifications.
4. User Survey: In order to have a well defined and useful product specification it was necessary to make contacts with and procure information from sources who are potential users and possible customers for the proposed system to identify their needs. This was achieved through visits to pulmonary function laboratories and discussions with physicians and technicians.
5. Competitive Analysis: A comparative evaluation was made of all products and systems now being marketed by manufacturers and system houses that cater to the pulmonary function laboratory market. This helped establish the functional limitations and drawbacks of these existing systems, and determine

the nature of product differentiation that would be required and could be achieved to make the proposed system desirable to the customers.

6. Coordination with Outside Consultant: This phase involved making suggestions as to how an outside consultant could help define the proposed product, and assimulating information gathered by a health care consultant regarding expected market trends, user profiles and product possibilities.

Once all of the above information was gathered, it was used to prepare a Pulmonary Function Testing Laboratory System functional specification which contained the following components:

1. Definition of the application area.
2. Identification of the application environment and personnel using the system.
3. Identification of instruments required to make necessary measurements.
4. Definition of primary and derived test parameters of interest including methods of their determination.
5. Outline of the signal conditioning and data processing requirements.
6. Identification of operator interface requirements.
7. Discussion of the data presentation requirements.
8. User survey data.
9. Competitive analysis results.
10. Outline of a possible product concept.

The system was conceived to be modular in nature so that it could be built up to handle test data obtained from most commonly used clinical procedures for pulmonary function testing. It would use a pneumotachometer as the flow transducer and would utilize a microprocessor for data analysis. Its most distinctive feature would be the on-line mass spectrometer used as a real time respiratory and blood gas analyzer. At present, there are no commercially available systems which can handle ventilatory flow and volume measurements together with on-line blood gas analysis within one system. The functional specification report as presented to TID appears in Appendix I. It also includes a detailed functional specification for a pneumotachometer flow-to-pressure-to-voltage transducer. This project was completed within the projected time limits.

Further work on the pulmonary function laboratory system was deferred due to adverse marketing data. It seemed from these reports that the pulmonary function testing market already had a large number of well established competitors vieing for a rather slowly growing demand. The marketing group concluded that under the present circumstances, the development of a product for this market would entail a high business risk.

There was an opportunity stemming from this project to make a presentation on TID's needs for medical transducers to a corporate research group. The Solid State Electronics Center (SSEC) was interested in knowing whether TID could utilize any of its expertise in pressure sensors for manufacturing medical transducers.

VCG Option for MEDDARS

This assignment required the implementation of a vectorcardiography (VCG) option for the existing Honeywell MEDDARS System. This medical monitoring system was designed to be a versatile 6-channel instrument capable of accepting data from a variety of transducers, computing and analyzing it and displaying the data graphics and alphanumerics on a multichannel, non-fade oscilloscope. The system also has a hard copy recorder (Visicorder) which can make permanent graphic records of the information presented on the display. A microprocessor option is available for system management and data analyses. A dual floppy disc system option allows storage of data and application programs. The system now has ECG, ECG/Rate, ECG/HIS, Blood Pressure, Differential Pressure, Temperature and general purpose Interface signal conditioning modules. The display unit is capable of generating and displaying X-Y pattern designed especially for vector loops. This particular assignment was to design the lead compensation network for vectorcardiography for the most acceptable lead system.

The first task was to carefully study the MEDDARS design, since the VCG adaptor unit had to be compatible with it. The unit had to accept data from a patient isolator unit which had already been designed and its output goes to the MEDDARS system for conditioning and display. A comprehensive survey was required of current literature and users to determine what test procedures were presently being used in clinics and hospitals. A questionnaire (Figure 4) was planned for circulation among field salesmen to obtain user opinions. It is important, in the design phase, to ensure that the system is designed

1. Do you, at present, use VCG in your lab/clinic?

   _____ Routinely _____ Often

   _____ Seldom _____ Never

   Would you like to have VCG capability?

   _____ Yes _____ No

2. Which lead system(s) do you like to use?

   _____ Frank _____ Cube _____ Tetrahedral

   _____ Axial _____ Others(s) _____

3. Which loop(s) do you prefer to analyze?

   _____ P-Wave _____ QRS - Wave _____ T - Wave

   _____ Cardiac Cycle _____ All of the Above

   _____ Others (s) _____

4. How do you define the E-point? _____

   _____

5. Do you need the origin of the loop to be identified with a marker?

   _____ Yes _____ No

6. Is one sagittal view of the loops adequate for your needs?

   _____ Yes _____ Left Sagittal _____ Right Sagittal

   _____ No

7. Additional Comments: _____

   _____

Name: _____ Hospital/Clinic: _____

City: _____ State: _____

Telephone No. _____

Figure 4. Vectorcardiography Questionnaire

according to existing federal and other standards. A survey was therefore made of existing ECG/VCG standards. Other commercially available systems were studied to determine how they have implemented these requirements.

The survey of available literature and user requirements and the results from the questionnaire showed that there is some controversy in the type of lead system used, the definition of the E or origin point, and as to whether the left or right sagittal views are more meaningful for clinical use. Based on the above information, a report was prepared showing alternative approaches that could be taken to satisfy most of the requirements. This report was presented to the Medical Marketing Manager for his review and approval. The actual design of the unit started after his approval. It was decided that the unit would accept inputs from a seven lead Frank lead system. The origin of the loop would not be marked and the right sagittal view would be displayed. The left sagittal view would be available with operator intervention. During the design phase, problems were encountered since the required adaptor box had to fit between an existing ECG/VCG isolator and the ECG signal conditioning modules and was required to have signals necessary to drive the Super X-Y (loop) display circuitry.

The basic design concept is shown in Figure 5 and was made to meet the functional requirements identified. It was strongly influenced by the preliminary performance specifications being outlined in the F.D.A. ECG/VCG Standards. The circuitry consisted of a

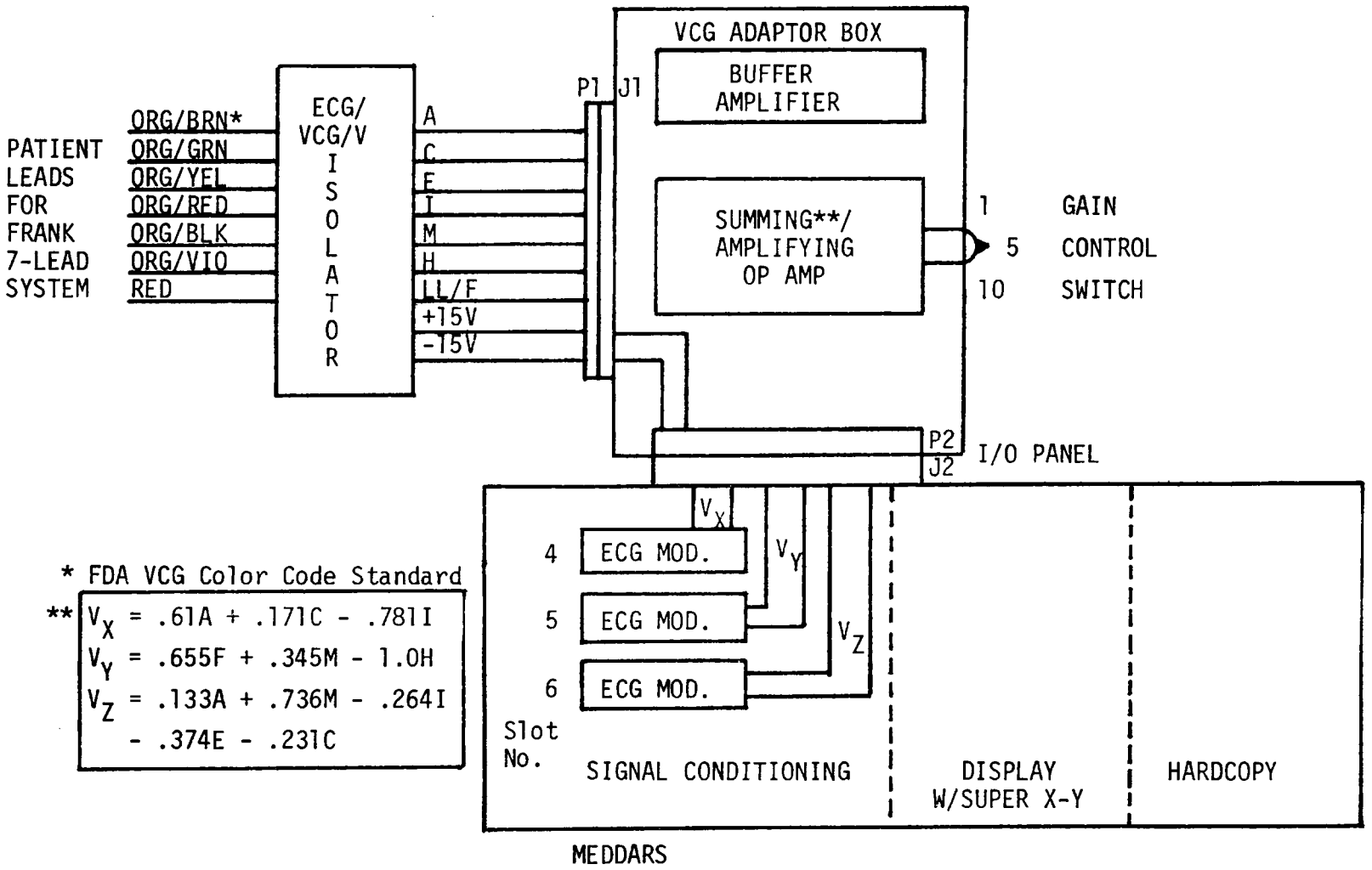


Figure 5. Vectorcardiography Design Concept

lead compensation resistance network for the Frank lead system and a summing and variable gain amplifier for controlling each of the three orthogonal signals. The signal amplification was necessary to obtain the proper sizes of VCG loops on the display and hard copy units for selected segments of the cardiac cycle like the "P" or "T" waves. The input to this unit was a.c. coupled in order to reduce the d.c. offset voltage from the isolator.

A breadboard unit was built with available components and hardware. Physically, the unit is conceived to be a plug-in which could be connected to the ECG isolator connector on the MEDDARS back panel. The system operator will need to reach the unit only to change the gain settings.

The prototype unit was tested as a stand alone unit with d.c. and phase shifted a.c. signals and was found to be functioning as expected. It is still necessary to test the unit after incorporating it with the MEDDARS system.

Thermal and Dye Dilution Programs for MEDDARS

This task involved defining the functional requirements for calculating cardiac output by the thermal dilution and dye dilution techniques of a cardiac catheterization laboratory.

One of the major projects in Medical Engineering is the development of application software for cardiac catheterization which will be an option for the MEDDARS system. The software is being developed for the CP-1600 microcomputer system. This task required determining the most widely used procedures for calculating cardiac output by the

thermal and dye dilution techniques which could be implemented as part of the application software package. It was already decided that the temperature and dye concentration data from the thermistor bridge and the densitometer respectively, would be introduced into the system through the all purpose Interface module.

This task first required a literature survey to establish the current status of the various methods used for measuring cardiac output by these two techniques and determining which particular method would receive user acceptance. The selected methods had to be easy to implement on the CP-1600 microcomputer and as far as possible, use the already developed and coded mathematical library. For system efficiency, trade-offs between analysis time and accuracy were continually evaluated. The software designers, for example, wanted to avoid any time consuming calculations of exponents. The study also included a survey of methods used by other manufacturers.

Two separate functional requirement reports, one for the thermal and the other for the dye dilution technique, resulted from the study of current literature and product brochures of other manufacturers. These reports will be used by the software engineers to add the respective data analysis capabilities to the MEDDARS 300 system as part of the cardiac catheterization laboratory application programs package. The reports included recommendations for implementing the calibration, data sampling, analysis and reporting procedures. They provided information on the sources, types and magnitudes of the input data. They also included cautions on types of problems that may be encountered when the Interface signal conditioning modules are used as

the data input stage to the MEDDARS from the thermistor bridge and densitometer outputs. The detailed specifications which were sent to the marketing group for approval appear in Appendix II.

MEDDARS/CCLS Interconnect Sales Order

This involved a sales order which required the design and fabrication of a custom-built interconnect system.

Charlotte Memorial Hospital had a Honeywell 316 minicomputer based Computerized Catheterization Laboratory System (CCLS) and a Honeywell 5600 portable tape recorder. Recently, they purchased a MEDDARS 200 system for the same laboratory. It was necessary to connect the MEDDARS to the CCLS computer to enable the system to collect data from the MEDDARS and store it in the 316 computer. As the MEDDARS 200 does not have any application programming capability, this would allow the data collected at the MEDDARS to be analyzed in the 316 computer. They wanted to record the data from both the MEDDARS and the CCLS in their 5600 tape recorder and to reproduce data from it at either terminal. The calibration signal generated in the pressure signal conditioning modules in the MEDDARS had a shorter duration than that required by the CCLS analysis program. Thus, a CCLS compatible calibration signal had to be generated at the MEDDARS terminal. The last component was a remote 5600 tape controller at the MEDDARS site. The job was already estimated for time and cost by another Applications Engineer and had to be completed within that estimate.

There were several required tasks for its completion:

1. Design of the interface cables based on the actual location of the units and interfacing with existing connectors.

2. Design of the signal switching units and the calibration and tape control box.
3. Getting the sketches of the circuits and mechanical fabrication drafted.
4. Ordering required parts from plant stock and outside vendors.
5. Getting mechanical fabrication done by the Model Shop and electrical circuitry built by Custom Production.
6. Testing the units and cables for proper functioning.
7. Getting Quality Control to approve the unit.
8. Shipping the unit together with installation and checkout instructions for the field maintenance staff and operation protocol for the customer.

Customer acceptance and proper functioning of the unit built within the time and cost limits were the final test for the project's success.

The system was designed and fabricated within the prescribed time limits. It consisted of a signal switching unit, a calibration and tape remote control box and a set of 14 interconnect cables. It was completely tested for proper functioning with a MEDDARS unit and a 5600 tape recorder.

It was then checked by a quality control personnel and was certified for shipping. It was shipped together with schematics, installation instructions and operation protocol to the customer before the projected date and was successfully installed at the Charlotte Memorial Hospital by a Honeywell service technician. A cable diagram for the system appears in Figure 6. The circuitry is being used and is

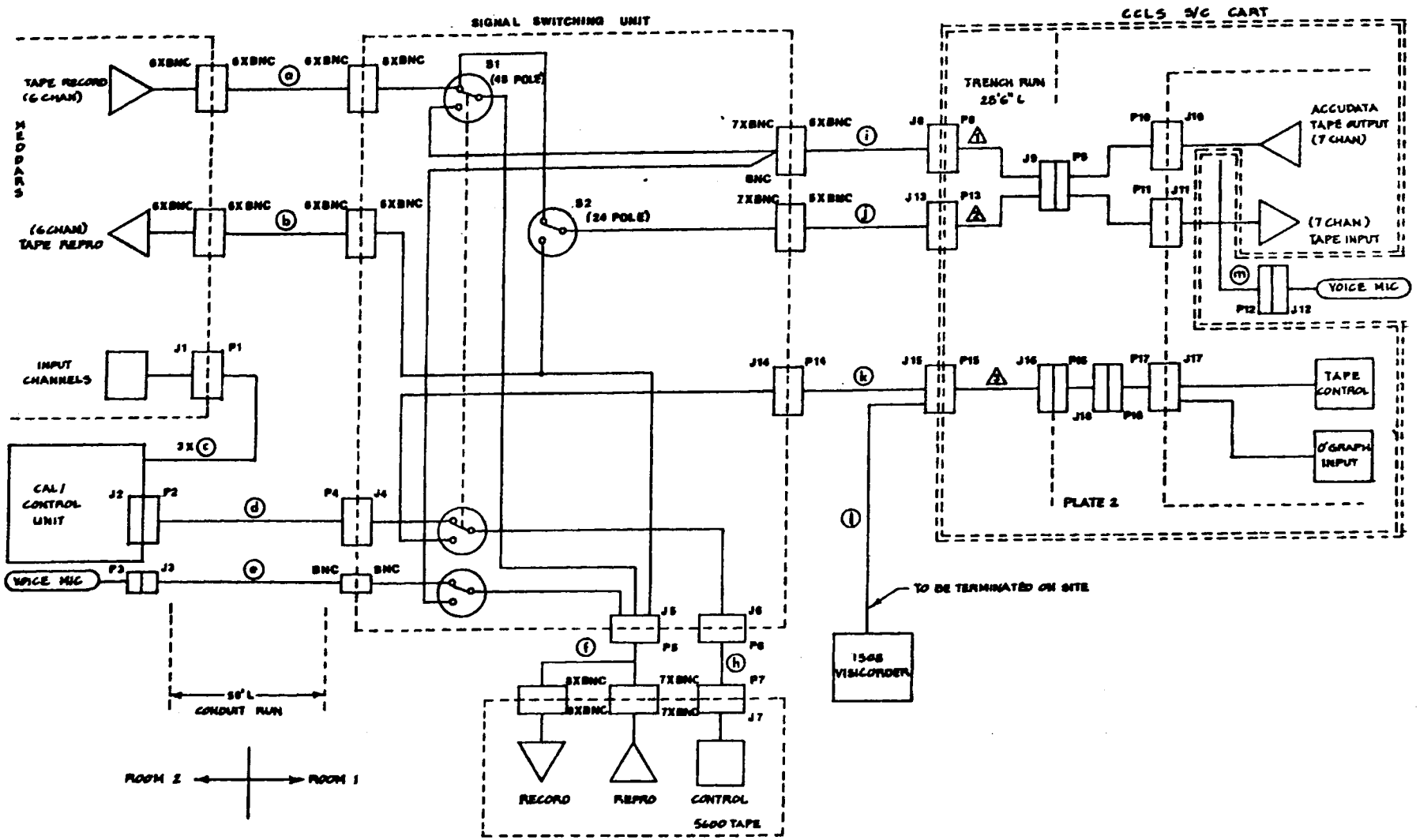


Figure 6. MEDDARS / CCLS Interconnect Cable Diagram

understood to be functioning as desired. The cost for completing this job was 89.5% of the projected LBM (labor burdened material) cost in the sales proposal. This would translate to a 24% profit on the job as opposed to the 15% profit usually anticipated within the division for custom built products.

Although the design of the unit did not require a great deal of technical expertise, the total project was very educational as it had all the complex requirements of documentation and testing before any unit can be shipped out of the factory. It was also interesting to control the cost of the unit within the set limit and there was some problem encountered in having the unit fabricated by the Model Shop. It was very difficult to check how many hours were spent in any part of the work in the shop and the total hours tend to exceed an estimate by a large percentage unless the Shop Supervisor commits to it in writing.

Mass Spectrometer Evaluation

A quadrapole mass spectrometer, known as a Pulsed Gas Analyzer (PGA), was developed under a government program by the Corporate Research Center (CRC). TID was approached by CRC to determine whether the devise had any marketing potential through the division. Within TID, the most obvious place for the use of a gas analyzer was as a medical instrument. This assignment was to evaluate the PGA to determine its possible application as a medical gas analyzer. The PGA derived its name due to its unique patented inlet system which introduces only minute samples of the test gas into the ionization chamber.

This inlet method allows the building of an instrument which is both small in size and weight and requires small sample volume. The last quality can be very useful when conducting on-line blood gas analysis. It is claimed that the instrument has the capability of detecting trace amount of gases and a fast response over a large atomic mass unit (amu) range but had little operational data to back its claim. The task was to study the operating manual, get the unit started up and operational, and devise a way to quantify its performance characteristics. The end result of this project was to develop an engineering and clinical evaluation plan for the instrument in conjunction with an outside consultant. This would establish the performance characteristics of the instrument and determine its potential as a medical gas analyzer.

The Pulsed Gas Analyzer was made operational and studies were initiated to quantify its performance. This included a study of the unit and its operation as well as a careful review of the principles of mass spectrometry. Commercially available mass spectrometers have, till now, found limited use in medical laboratories. A comparative analysis was made of these medical gas analyzers to determine why they are not selling well. It appears that most mass spectrometers available today are large units, which are difficult to operate, have cumbersome calibration procedures, and are very expensive ($25,000).

The PGA has several features which make it more attractive than other systems available today: (a) it is a compact unit; (b) it needs small samples of test gas, making it ideal for blood gas analysis;

(c) it can be made semi-automated for calibration and operation; and,
(d) it can be built to sell for less than $18K.

The unit could be used as a respiratory and blood gas analyzer in pulmonary function testing, intensive care and stress testing laboratories and as an anesthetic gas analyzer in a surgical suite.

An engineering and clinical evaluation plan was developed for the unit in conjunction with the University of Colorado Medical Center in Denver. Details of the engineering evaluation plan appears in Figure 7. However, the entire project was cancelled after a marketing study by an outside consultant concluded that there is a very limited market for the mass-spectrometer type of medical gas analyzers.

Sales Proposals

It is necessary from time to time to prepare proposals for customer requested units which extend the standard capabilities of existing products to meet specific requirements. They all involve understanding the requirements, making a preliminary design of the system and writing up the anticipated operation protocol. The next phase involves estimating, in detail, the labor and material required to complete the job and determining the time required to finish the fabrication of the unit after receiving the order (days ARO). The estimates must be priced by the accounting staff and sent to the marketing group where the requests for the sales proposals usually originate. If the marketing personnel find the proposals acceptable, they forward it to the customers.

ENGINEERING EVALUATION

This phase of evaluation is intended to establish baseline performance characteristics of the pulsed gas analyzer. The evaluation should determine, in both the sweep and program mode, the following:

1. Warmup time for the instrument for stability of output within $\pm$ 1%.
2. Output stability over a 24 hour period after initial warmup.
3. Repeatability of output response over a 30 day period.
4. Response time of device: (a) rise time to 90% steady state output; (b) lag time.
5. Instrument accuracy for gas analysis expressed in volume percentage when measuring gases of clinical interest - O_2, N_2, CO_2, Ar, N_2O, He.
6. Sensitivity of the instrument - minimum determinable gas concentration.
7. Signal to noise ratio for instrument.
8. Sampling flow rate: minimum flow rate required to achieve optimum accuracy.
9. Optimum pulse rate for pulse inlet system for stable operation.
10. Optimum sweep speed for a given amu range (2-50 amu).
11. Calibration requirements for the system.
12. Frequency at which calibration procedure has to be repeated.
13. Failure of any component in the instrument.

The engineering evaluation is anticipated to take 6 weeks. After its completion, the following questions should be addressed:

1. Does the system, in its present form, or with electronic modification, perform adequately as a medical (respiratory/blood gas) analyzer? What are its weaknesses and how could they be eliminated?
2. What are the critical functional requirements for a medical gas analyzer?
3. Did any component fail during the evaluation period?
4. What is the estimated product cost? How does it compare with other medical gas analyzers?
5. If the system has adequate basic capabilities, what should be the next phase of (application oriented) evaluation?

Figure 7. Pulsed Gas Analyzer Engineering Evaluation Plan

During the internship period, four such proposals were prepared for marketing: (a) MEDDARS Audio Alarm; (b) Mini-Med S/C Housing with Power Supply; (c) Thermal-Dilution Option for CCLS System; and (d) APUFS System.

MEDDARS Audio Alarm. At present, the MEDDARS has only visual alarm signals (light) which responds when the heart rate or blood pressure (arterial or ventricular) goes beyond preset high or low limits. Scott & White Hospital purchased a MEDDARS 100 system for use as a patient monitoring unit in their intensive care unit (ICU). They wanted audio alarm signals when extreme limits of the parameters were reached. The alarm unit would be located outside the patient's room (in this case, an ICU) so that it can be heard by nurses at the central station.

The sales proposal for the MEDDARS Audio Alarm was sent to marketing and was reviewed by marketing. However, it was not quoted to the customer as the overhead expenses, especially for initial design and detailed documentation, pushed its sell price to unrealistic levels. This unit could be sold only when built in quantity so that the development cost can be distributed.

Mini-Med S/C Housing with Power Supply. This was a sales proposal for a three module signal conditioning housing with built-in power supply. The unit would hold three MEDDARS signal conditioning units and its channel outputs would be available for display as analog waveforms on a three channel display unit. The alarm signals would also be available for use. Its potential use would be as a simple,

single patient, bedside patient-monitoring system. Such systems could be sold at a much lower cost than the total MEDDARS system.

There was some interest in offering this unit as a standard MEDDARS option. Therefore, the proposal also required an incremental cost analysis for additional units built after the first four.

The proposal is being reviewed by marketing. The decision for its acceptance is still pending. The incremental cost analysis showed that it is cost effective to build 5 units or over 24 units.

Thermal-Dilution Option for CCLS System. This was a proposal for adding a thermal dilution option to an existing Honeywell 316 based Cardiac Catheterization Laboratory (CCLS). This option would require a thermistor bridge network and associated circuitry that can interface with an Accudata 113 Bridge Amplifier unit. The other part of the proposal was to outline the thermal dilution calibration and data analysis program for calculating cardiac output which could be added to the 316 application software package. The estimate of cost was for the thermistor adaptor box and for writing the new computer software program and incorporating it into the existing 316 minicomputer at the customer site.

The sales proposal was completed and sent to marketing. It included both software and hardware components and was designed to interface with existing equipment in the laboratory. It was reviewed and found acceptable by marketing and was sent to the customer for their review and acceptance.

APUFS System. This task cannot be classified as a typical sales proposal. The Tri-Service Pulmonary Physiology Group of the Armed

Forces has prepared an Automated Pulmonary Function Testing System (APUFS) specification. It was proposed that this standard system would replace all existing testing systems in pulmonary function laboratories in hospitals and clinics run by the Armed Forces within and outside the U.S. This would provide a uniform testing regime for all the laboratories enabling easy patient and data transfer and centralized software development and purchasing of all equipment. The Tri-Service Group approached Honeywell to help them develop part or all of the prototype systems.

The task involved studying the extensive specifications document and determining whether TID could meet any portion of the requirements with existing equipment. It also required determining whether any new development undertaken by TID for this project would benefit TID in terms of its future product plans. The recommendations had to be presented to the marketing group and members of the Tri-Service Group.

After thoroughly understanding the proposal, specific recommendations were made to the divisional marketing and sales personnel and then to the Tri-Service Group representatives. The implementation of the total proposal was a very large venture and, in all honesty, was an overkill for day-to-day clinical testing of pulmonary diseases. It is doubtful that any similar system would ever be conceived again. Marketing decided not to pursue this further as it felt the division had little to gain from any such development collaboration and because the Tri-Service Group wanted TID to be more than a simple OEM vendor selling already developed products. It is now known that the complete project did not get funding from the Defense Department.

CHAPTER IV

DESCRIPTION OF OTHER ASSIGNMENTS

Throughout the internship period, there were opportunities to attend top management meetings, presentations and discussions and to interact with various groups and individuals from both within and outside the division. Some of the activities had direct bearing to specific projects while others gave an opportunity to look at how the division functions. This chapter describes these activities.

Interactions with Outside Consultants

From time to time during the internship period, it was necessary to consult engineering, marketing and medical experts from outside Honeywell regarding various projects. Specific activities are outlined below.

1. Attended several presentations made by an outside Health Care consultant on his evaluation of possible opportunities for TID to market new medical products. His presentations included evaluation of requirements in terms of user groups, current products and suppliers, and trends in specific markets including anticipated market sizes and factors that might affect it. This information was weighed before preparing functional specifications for new products. It was also helpful in understanding the medical instrument market place.
2. Worked closely with the Biomedical Engineering Department and surgeons and anesthesiologists of the University of Colorado Medical School to explore the possibility of clinical

evaluation of MEDDARS and the Pulsed Gas Analyzer. The systems would be used in the surgery room and in the pulmonary function laboratory in the hospital.

3. Visited several hospitals and clinics for meetings and consultations with physicians, technicians, and other users of medical products. These meetings were utilized to determine the user requirements for pulmonary function testing, surgical monitoring, cardiac output calculations, VCG measurements and other application areas. The visits also included tours of existing facilities.

Interactions with Other Honeywell Divisions

The internship position provided several opportunities to interface with engineering and marketing personnel of other Honeywell divisions. The following are some examples of such activities:

1. Interacted with Honeywell's Solid State Electronic Center (SSEC) to study their capabilities and to determine if any of their technological know-how can be utilized in the medical instrumentation market. This study included a visit to SSEC's solid state device manufacturing plant in Colorado Springs, talks with their design and marketing personnel, and preparing functional specifications for silicon strain gauge pressure sensors that could be used in medical transducers.
2. Interacted with Corporate Research Center to gain information on their quadrapole mass spectrometer which was of interest to TID and to follow the course of clinical evaluation of one of these units.

3. Attended presentations by the Information Systems (HIS) Group. The purpose of this meeting was to acquaint TID personnel of the medical data compilation and computation capabilities of the group with an aim to avoid duplication of effort within the company and enhance development of co-operative programs.

Management Meetings

There were several opportunities during the year to attend top level divisional meetings as an observer which gave an insight into the working of the division. They consisted of:

1. Attending several of the Factory Operating Manager's (FOM) meetings which are held every month. These meetings allow the production managers of the four product lines to report separately on the activities and progress of their operations to a top management committee including the general manager and heads of the production support groups. Topics discussed in these meetings include the production schedule status, backlog and bookings for each product, costs and expenses breakdown, raw materials and inventory status, manpower plans and their present efficiency and areas of present or anticipated future problems.
2. Attending the Medical Engineering Program Review Meeting which is held every month. In these meetings, the Medical Engineering Manager reports on the progress of all the design and development projects under his control to a top management group. The group is comprised of the general

manager, heads of marketing, sales, production, testing, and other support groups. Topics covered here include status reports on the individual projects in terms of time and resources (both monetary and manpower), and present and anticipated problem areas for the projects.

Courses and Seminars

During the course of the internship there were several occasions to attend in house courses and outside presentations. Examples of this type of activity follow.

1. Participated in the MEDDARS Sales Training program which was designed for the field sales staff where detailed presentations were made of the capabilities of this system by design engineers. Anticipated customer questions were answered and participants were allowed to operate the system independently during this week long course.
2. Attended two week long customer training courses on Honeywell's Model 5600 medium band portable and Model 96 wide band laboratory magnetic tape recorder systems. These courses are designed for customer representatives who are directly involved in using and maintaining instruments. The courses covered the basic principles of analog (direct and FM) recording and the operation protocol for the systems, and conducted a step-by-step analysis of their startup, calibration and maintenance procedures. Extended capabilities of the systems, their critical components and field servicable parts were identified

during the course. The participants also get a chance to work on the specific instruments.

3. Attended a course titled "Problem Solving" which was offered by Corporate Training Department in the TID plant. This course analyzed methods for solving job related problems, both technical and non-technical in nature. The general method outlined involved setting goals, creating and evaluating alternatives, planning, organizing and controlling chosen alternatives and analyzing deviations of results from set goals. The problem solving approach was illustrated by simulated problems.
4. Attended the National Society of Cardio-Pulmonary Technicians (NSCPT) conference in Denver. This conference gave an insight into present status of research and available products in the fields of cardiology and pulmonary function testing, and provided an opportunity to establish contacts with Denver area Pulmonary Function Laboratory personnel.
5. Attended Beckman Instruments Seminar on Cardio-Pulmonary Stress Testing presented in Denver. It consisted of two presentations, one on cardio-pulmonary stress testing methodology and the other on metabolic measurements during stress. This was followed by a demonstration of Beckman's Metabolic Measurement Cart and their new ultrasonic spirometer.

Meetings with International Marketing Staff

The internship position provided the opportunity to meet with several members of international marketing in view of probable future

employment with Honeywell in its Indian subsidiary. Details of two of these meetings follow.

1. Had extensive discussions with TID's International Marketing Manager on marketing techniques applied by the division overseas. Discussed the various methods of handling international sales orders, types of divisional products that have done well overseas, necessary paperwork and customs clearances required and usual problems encountered such as difficulty in, or lack of, communication.
2. Had a detailed discussion with the Market Manager for TID products in Honeywell Europe Division, headquartered in Brussels, Belgium. The Europe Division includes all of Europe (including Communist Europe), the Middle East and North Africa. He explained the organization, territory, location, and working of that division. He also discussed typical problems faced by employees of Honeywell International and pointed out how resourceful and independent field personnel outside the U.S. have to be.

CHAPTER V

GENERAL OBSERVATIONS

Internship Experience

The total internship experience was very educational and worthwhile. It was definitely the highlight of the Doctor of Engineering program. It gave me an opportunity for a close look at the operation of a profitable and stable industrial organization. It was also extremely fortunate that the management at TID made every effort to assign tasks which were non-trivial in nature, educational to the intern and yet useful to the company.

The most important lesson learned during the internship period has to be the realization of the importance and strength of the marketing group within Honeywell. It appeared that the destiny of the Test Instrument Division was largely controlled by this group. The staff of this group identifies new product and sales possibilities, makes initial decisions on possible product developments and on the final shape, form, and capabilities of new products to be released to the market. Coming from a purely academic engineering background, one tends to develop the impression that any improvements in the capabilities of a product through technical advancement should be acceptable to the marketplace. Therefore, it was difficult to understand a back seat role for engineering to marketing in a company which sells sophisticated and advanced technical knowledge. However, after a year of internship training, it was possible to understand the necessity for such an arrangement within a division whose success is rated by its

profitability. This simple realization probably made the entire industrial experience worthwhile.

Doctor of Engineering Program

The electronics instrumentation manufacturing industry, in general, is quite uninformed about the Doctor of Engineering program. They are at a loss when it comes to understanding how an intern could be best trained and utilized or where such a graduate can ultimately be placed within the present organization structures. Graduates with Doctor of Engineering degrees are overqualified to be offered positions of entry level design engineers and are probably not quite qualified to assume supervisory roles, since they are not familiar with the company organization. Only time, entry of a large number of Doctor of Engineering graduates into industry and the success of the early graduates, can help alleviate this problem. More industrial participation in the development of the program would be very useful. It should be noted that once people in industry understand the program, they seem to approve of it.

Medical Instrument Market and Honeywell

The internship period also provided several opportunities to learn about the medical instrument market which has some unique traits. The customers, who are usually physicians or medical laboratory directors, seem to have a rather wide range of views as to what any particular instrument should do. These slightly varying requirements, especially for data analysis, make the selling of any standard, inflexible medical data recording system rather difficult. This has

produced a segmented market which has a large number of small companies which appear and disappear all the time. A large number of bigger companies have tried to enter the market with a single product which was an offshoot of their existing established product lines without carefully studying the marketplace. There seems to be a small but growing resistance among users against instruments which move the physicians away from the patients. The fast rising cost of medical care and the continuous threat of more and more federal and state regulations aimed at controlling costs and setting more rigid safety standards make the future for elaborate and expensive systems bleak.

All this leads to a mixed outlook for the future of the medical instrumentation market. On one hand, increasing expectations of the public from the medical community and increased costs for experienced medical personnel seem to suggest significant growth for automated medical instruments and systems. On the other hand, concerns over growing costs and tighter government regulations point to the direction of slow growth. The result is possibly the emergence of a market which will accept only superior products built without frills which minimizes human intervention and are manufactured by large companies that have the resources to fund the extensive test procedures to comply with federal and state regulations. However, this will probably happen only after an unsteady market for 3-5 years when most of the small companies will disappear, and companies with sales over $7-10 million will have to grow or face acquisition by larger companies, or disappear altogether. The larger companies and medical divisions of large corporations can survive only if their corporate managers are

committed to be in the field and are prepared to take losses for the next few years and are ready to make selective acquisitions of smaller companies. They must also have an aggressive marketing force with persons specialized and trained for medical marketing.

MEDDARS, TID's latest offering to the medical market, is an outstanding design achievement and yet for several unrelated reasons, it has not reached the anticipated success in the market. Honeywell, with its limited offering to the medical instrumentation market, has yet to gain easy recognition and confidence of the customers. MEDDARS has a large number of features in its basic format which cannot be utilized in a truly small clinic environment. MEDDARS 100, in the minimum configuration, is not cost competitive with other simple physiological data collection systems. There are probably two solutions, which are not exclusive of each other, that could be undertaken to get the maximum return of the development cost for the basic design. The first is to build more signal conditioning modules and application program packages to make MEDDARS useful in other application areas outside cardiology. The other course would be to utilize the existing signal conditioning modules and develop low cost display and hardcopy units which have much less capabilities than the existing systems and package them as a low cost physiological data recording and display system.

The other medical instrument offered by TID is the ACS-1000, which is a semi-automatic white blood cell counter. This has similar problems to those of MEDDARS in that it exists as a sole offering to

the clinical instrumentation market. On the other hand, TID has had great success as an OEM vendor in the medical market with their VISICORDER oscillographs. The Metrology group, with over 200 hospital instrumentation service contracts, is the fastest growing segment of business within the division.

As a corporation, Honeywell seems to be committed to remain in the medical market for a long time. To ensure this, they can take either or both of two courses of action. The first would be to develop new products of their own. Logical places would be to develop products which utilize the basic capabilities of MEDDARS and products for the clinical instrument markets. The other approach would be to acquire companies with technically sound products. They could market these acquired products for a couple of years and develop the next generation replacements for them.

One interesting possibility would be to see how a separate medical instruments division would function. There are several advantages to have it as a part of a successful and highly profitable division like TID. However, it is also a curse as the divisional marketing group tends to hesitate to invest money in the unprofitable product lines when they see better return on investments on its traditional product lines. If there is a medical instruments division which has to justify its existence by showing profits, the marketing group would have to be very aggressive in pursuing new product developments to ensure its very survival.

The divisions of Honeywell operate as individual profit centers. They have to continually justify their existence with profits or face

extinction. During the internship period, the Photo Division was sold for lack of profits. The company also aggressively attempts to acquire new companies or product lines. This shows the dynamic nature of the organization which is essential to its long term growth and stability. There were also several changes within TID. Most of them occurred due to two moves; the Medical Systems Center (MSC), which was a venture group in Minneapolis, was moved to Denver and merged with TID. This helped locate all of Honeywell's medical instrument offering in one location and under one management. This has to be considered as a move in the right direction. A small group of design and development engineers from the now dissolved Photo Division were relocated to TID. In addition to this, frequent changes within the plant depicted a fascinating picture of a continually changing industrial organization.

APPENDIX I

PULMONARY FUNCTION LABORATORY SYSTEM

This appendix contains the functional specifications for a Pulmonary Function Laboratory System as it was submitted to TID. A preliminary report was submitted in January, 1977. However, two weeks after its submission, the marketing group decided not to pursue the development of a Pulmonary Function Laboratory System due to adverse marketing study reports.

The report was revised in June, 1977 in order to preserve the information for future reference by the company.

Honeywell Interoffice Correspondence

Date: July 20, 1977

To: Stan Edwards - 215

From: Ron West - 255

ation: TID - Denver

bject: PULMONARY FUNCTION LABORATORY SYSTEM

cc. Jack Baring - 204
Ira Langenthal - 209
Don Smith - 215
Milt Womack - 214

Deb Sengupta has completed a study of the application requirements for the subject system. This work was a requirement of his Doctor of Engineering internship. I feel that the information collected is potentially quite valuable and therefore have attached a copy for your information. Since Deb has already left TID please direct any questions you may have to me.

R. E. West

RW/mhf
attachment

PULMONARY FUNCTION LABORATORY SYSTEM

- Preliminary Functional Specification

D. SENGUPTA
January, 1977
Revised-June, 1977

ABSTRACT

In recent years, there has been an ever increasing public concern over lung diseases due to breathing of polluted air and smoking of cigarettes. This has greatly increased the research and clinical effort in the field of Respiratory Physiology. This opens up a unique opportunity for the Test Instruments Division to enter this medical market segment with a microprocessor-based Pulmonary Function Lab Testing System. This will broaden significantly the medical market base for T.I.D. as instruments used in respiratory function testing is not the same as those used in the cardiology field which it now caters to. The introduction of this sytem will also help change the image of T.I.D. as being a one product medical instrument manufacturer. Although there are several other manufacturers already in this market, there is still room for a product which utilizes systems design expertise and has simple and inexpensive gas analysis instrument.

This document describes a pulmonary function lab system which is modular in nature and can be built up to a system that covers every popular aspect of pulmonary function testing. The unique feature of this microprocessor-based system is the incorporation of an on-line mass spectrometer which is designed around the Pulsed Gas Analyzer developed by the Corporate Research Center.

CONTENTS

CHAPTER I

SUMMARY

Respiratory capacity of humans is analyzed by pulmonary function tests which measure functional relationships between various parts of the pulmonary anatomy, central to which is the lung. These tests are useful in the diagnosis of respiratory disorders and in guiding therapy of patients with suspected cardiopulmonary diseases. They are valuable in deciding whether a patient is fit for surgery and are used in epidemiological surveys to access hazards or simply to document the incidence of disease in a community.

In terms of user groups, Pulmonary Function Lab systems can be classified into:

(a) Screening devices used in physicians offices and in smaller clinics,

(b) diagnostic devices used in general hospital laboratories and in larger clinics, and,

(c) research and physiological evaluation devices used in large teaching and research hospitals.

The patients are usually referred to the lab by physicians not attached to it and the tests are conducted by pulmonary technicians who have adequate testing knowledge but little instrumentation expertise. The technicians work under the guidance of a pulmonary physician or a lab director. Therefore user convenience is an important consideration in the design of any system for this application area.

As opposed to physiological monitoring systems, Pulmonary Function Lab systems record results of tests which have short, fixed duration. The maximum time required to perform any one test is about seven minutes. The data of interest in the Pulmonary Function Lab have very low bandwidth (DC to 10 Hz). Therefore the required system performance is considerably 'slower' than 'typical' physiological monitoring systems.

The functional capabilities of a patient's respiratory system are evaluated by a series of tests. The primary parameters of interest in these tests are the flow rates, volumes and compositions of gaseous mixtures which are inspired and expired during the respiratory cycle. Details of these tests appear in Chapter III.

Spirometry tests are performed to determine how the gases get to and from the alveoli by the process of ventilation, forces that move the lung and chest walls and the resistances the gases have to overcome. The measurements for these tests are made by flow-to-voltage transducers (spirometry devices). Spirometry is the simplest and most popular test among all the Pulmonary Function Lab procedures. On the other hand, conclusions drawn from its results have a high degree of uncertainty associated with them.

The nitrogen washout test measures the evenness of dilution of alveolar N_2 by inspired O_2 to provide information about inequality of ventilation. This test can be performed by two methods - single breath and multiple breath,referring to the number of times the

subject inhales from a 100% O_2 source. This test requires a spirometer and a Nitrogen analyzer for its measurements. This test is usually never handled by screening devices.

The helium dilution test measures the rate at which added helium is diluted to equilibrium by alveolar gas in a rebreathing system to measure the efficiency of the ventilation process. The test results obtained from this procedure are very similar to those obtained by the multi-breath nitrogen washout technique. Therefore, except in large research hospitals, only one of these two tests is performed. The required instruments for this procedure are a spirometer and a Helium analyzer.

The diffusion capacity test measures the efficiency with which respiratory gases cross the blood-gas barrier and requires a spirometer and a CO analyzer for its measurements. This test procedure is rather involved.

The body plethysmograph test uses a large air tight box like a telephone booth (known as a body box) in which the subject sits for the test. It measures the total volume of gas in the lung including any that is trapped in obstructed airways. It also measures several lung volumes. The body box has to be calibrated by a complex procedure.

Blood gas analysis looks at the ventilation-perfusion inequality and how matching of gas and blood concentrations determine gas exchange. This analysis requires some kind of a multigas analyzer.

All the above tests do not have the same importance from the users' point of view. While the spirometry tests are the most widely used procedures, diffusion capacity test is conducted by only the more sophisticated labs. Quite a few users conduct either the nitrogen washout or the helium dilution tests but neither has emerged as being the more acceptable procedure. Body Plethysmography is a confirmatory test procedure which is used to substantiate results obtained thru spirometry, dilution and washout tests. Blood gas analysis is becoming more and more important and acceptable because the uncertainty associated with its results is very low. However it suffers from its invasive nature and from the lack of equipment at affordable prices. All the above facts force one to conclude that there is no one universally accepted and used test regime in the pulmonary labs. Therefore the design of equipment should be modular in nature so that the user has the choice of which instruments he wishes to use, and what test parameters he prefers to look at.

With changing equipments and test procedures, the data analysis requirements are also changing. Research continues to find more meaningful test procedures which have less variance in predicted normal values so that diagnosis can be more accurate. Therefore the system data analysis capability must be flexible enough to permit changes and upgrading as needed.

While patients who are being screened for possible cardiopulmonary diseases may pass thru the labs only once, those with known disorders are tested repeatedly to follow the course of the disease and effectiveness of the prescribed therapy. For the latter, trend studies of various test parameters are of extreme clinical importance. This dictates the need for devices to store patient specific data files.

A special requirement for this application area is generation of predicted normal values for several of the test parameters from established equations (Appendix A). The variables for these equations are sex, age, height, weight and body surface areas of the test subject and must be available to the system. In addition, several of the test parameters are collected at body temperature and pressures but have to be reported in atmospheric units. The system must have access to pressure and temperature data. Therefore there must be some device for operator entry of all such information.

Survey of available products in the market (Appendix D) reveals that several companies are engaged in manufacturing pulmonary function lab systems of varying sizes and configurations. The gas flow rates and volumes are measured by spirometry devices which range from water bell type to pneumotachometers. The respiratory gas concentrations are measured by an assortment of single gas analyzers or by stand-alone mass spectrometers. Body plethysmography analysis is done by stand-alone body boxes. Blood gases are usually measured off-line from a sample of blood extracted from the subject although there are two mass spectrometers which can do them on-line. Data computation and analysis are performed on a range of hardware from smart hardwired logic to minicomputer systems.

Systems available today can be classified into the following categories on the basis of their size and complexity.

1. Small screening devices capable of handling selected tests in spirometry and utilizing semi-pneumotachs and hardwired logic.
2. Medium size microprocessor based systems which can handle spirometry and helium dilution, nitrogen washout and diffusion capacity tests. The gases are analyzed in most of these systems by single gas analyzers. These are aimed at the medium-sized hospitals and clinics markets.
3. Large minicomputer based systems which have the capability of interfacing with any instrument. But they are rarely available with on-line gas analyzers for blood analysis. The system integration is also not optimum as they are tailored systems and they are very expensive.
4. There are four gas analysis systems (mass spectrometers) which are stand alone units capable of on-line analysis of blood gases.

Therefore, there is no commercially available unit which is capable of handling all the test procedures listed above including on-line blood gas analysis. There is also some concern among the users regarding the high errors in the flow rate values determined by existing systems especially at the two extreme limits of flow.

This document details the functional specifications of a Pulmonary Function Lab system which has the following significant features:

1. Flexibility, allowing for future accommodation of changes in test procedures.
2. Modular design, allowing basic components to be used to build both screening and complete testing systems.
3. A pneumotachometer which has been redesigned to retain all its attractive features but uses only one flowhead instead of four now needed to cover the complete flow range of interest within acceptable accuracy values.
4. On-line mass spectrometer for both respiratory and blood gas analyses allowing the elimination of several stand-alone gas analyzers now used. The on-line blood gas analysis eliminates the cumbersome off-line procedures used and brings the entire testing regime under one management scheme. The on-line analyzer also allows continuous monitoring of gases during spirometry. This enables the system processor to correct flow rate readings to give higher accuracy for the test parameters.
5. Optional mass storage device which allows future analysis of patient specific data.

A product concept and rationale is developed in Chapters IV, V and VI. The system consists of a pneumotachograph and differential pressure transducer for gas flow and subsequent volume measurements. An on-line mass spectrometer with a range of 4 to 80 amu is used for respiratory and blood gas analyses. A body box with associated control instrumentation is included for body plethysmography testing.

There will be three signal conditioning modules, one of which will have optional piggy-back extension cards:

1. Spirometry S/C Module:
    a. Basic spirometry test circuitry
    b. Optional helium dilution test circuitry
    c. Optional nitrogen washout test circuitry
    d. Optional diffusion capacity test circuitry
2. Body Plethysmography S/C Module.
3. Blood Gas Analysis S/C Module.

The analog data will be digitized, sampled and analyzed to give test parameters by an A/D converter, multiplexer and a microprocessor system. This system will also be responsible for automated calibration of the instruments, correction of flow rate data by gas concentration values, calculation of predicted normal values and generation of patient reports including trend plots.

The patient reports will be displayed on a graphic/alphanumeric display unit and copied for permanent record on a hardcopy unit. A function keyboard will be provided for operator entry of patient data and for keystroke programming. A mass storage device option will be available for storage of patient specific data files.

CHAPTER II
SYSTEM REQUIREMENTS

This section describes the general system requirements for the PULMONARY FUNCTION LABORATORY SYSTEM.

I. Primary Calculations/Tests:

- A. Spirometry Test
  - (i) Vital Capacity
  - (ii) Forced Expiratory Vital Capacity
  - (iii) Forced Inspiratory Vital Capacity
  - (iv) Flow/Volume Loop
- B. Body Plethysmographic Analysis
- C. Blood Gas Analysis

II. Optional Calculations/Tests:

- D. Nitrogen Washout Test
  - (i) Single Breath
  - (ii) Multiple Breath
- E. Helium Dilution Test
- F. Diffusion Capacity (of CO) Test.

III. Personnel:

Pulmonary Function Laboratory Technicians (PFT) usually run the tests under the supervision of a pulmonary function physician or laboratory director. The patients are usually referred to the laboratory by physicians not directly attached to the lab who receive the final report.

IV. Environment:

The tests are usually performed in a Pulmonary Function Laboratory which has normal lighting, temperature, humidity and pressure. The systems are seldom moved from one location to another. No special interference shielding is required.

V. Special Features:

A. The system will be used primarily by paramedical staff with extensive application knowledge but little electronic expertise. Therefore ease of operation is of primary consideration.

B. Calibration procedures for the pneumotachometer and the mass spectrometer require fixed concentration gas mixtures and are quite involved. Therefore they should be automated under system processor control with minimum operator intervention necessary. The body box will be calibrated by the technicians under processor guidance.

C. For operator ease, the test sequence should be preprogrammed. But to add flexibility, the operator should have the capability of deleting certain test steps he deems unnecessary.

D. Pulmonary function test results are largely dependent on patient effort. The only person capable of determining whether the patient is putting out enough effort is the Pulmonary Lab technician. Therefore once a test is completed, the operator must have the ability to review the data and accept or reject it on the basis of his judgement on amount of patient effort.

E. The operator should have access to a PRINT key which copies the complete information on the display screen on to a hardcopy for permanent record keeping.

F. The system must generate predicted normal values for test parameters from available equations.

G. The subject should be able to see the display screen during the maximum voluntary ventilation maneuver to enable him to maintain a constant rate of breathing. This is because the magnitude of MVV is a function of respiration rate.

H. There should be a small display screen in the body box displaying the panting rate (waveform) to enable the subject to maintain a constant panting rate. This is because the parameters measured by the body box are dependent on the panting rate.

I. Usually patients with known pulmonary disorders and under therapy are tested once every four to six weeks over a period of several months to evaluate their progress and the effectiveness of their therapy. Therefore, as an option, the system should be able to store patient specific data files in disks or cassettes.

J. The summary reports generated on a patient must be detailed and complete because the referring physician will have to make the disease diagnosis on the basis of this one report. There should also be capability for the operator to add some fixed text comments to the report.

VI. System Components:

A. Measuring Instruments:

(i) Pneumotachometer - consisting of a pneumotachograph and a pressure sensor.

(ii) Mass Spectrometer - with 4 - 50 amu range and 4 programmable channels.

(iii) Body Plethysmograph - consisting of a body box, box and mouth pressure sensors and control circuitry.

B. Signal Conditioning Modules:

(i) Spirometry Module: With basic circuitry for the spirometry test and piggy back extensions with front panel switching for helium dilution, nitrogen washout and diffusion capacity tests.

(ii) Body Plethysomograph Module: for that test.

(iii) The mass spectrometer has its own signal conditioning circuirty so that it can operate as a stand-alone product and therefore the Blood Gas test does not need a separate signal conditioning module.

C. Data Processor and Analysis System: With

(i) capability of sampling and digitizing data,

(ii) capability for calculating test parameters and predicted values,

(iii) interval timer,

(iv) capability for sending out control signals,

and (v) capability for generating summary and trend reports.

D. Display Unit: Capable of displaying system generated graphic and alphanumeric information.

E. Hardcopy Unit: Capable of copying any information on the display unit.

F. Function/Alphanumeric Operator Input Device: Capable of accepting information from the operator and sending it to the processor.

G. Mass Storage Device (optional) capable of storing patient specific data files.

Although there are no specific FDA standard for this application area, there are several groups trying to formulate requirements: They are:

American Thoracic Society:

Medical Devices Committee (Dr. R. M. Gardner, Chairman)

Pulmonary Spirometry Standard

- new, under preparation, to be completed in late 1976.

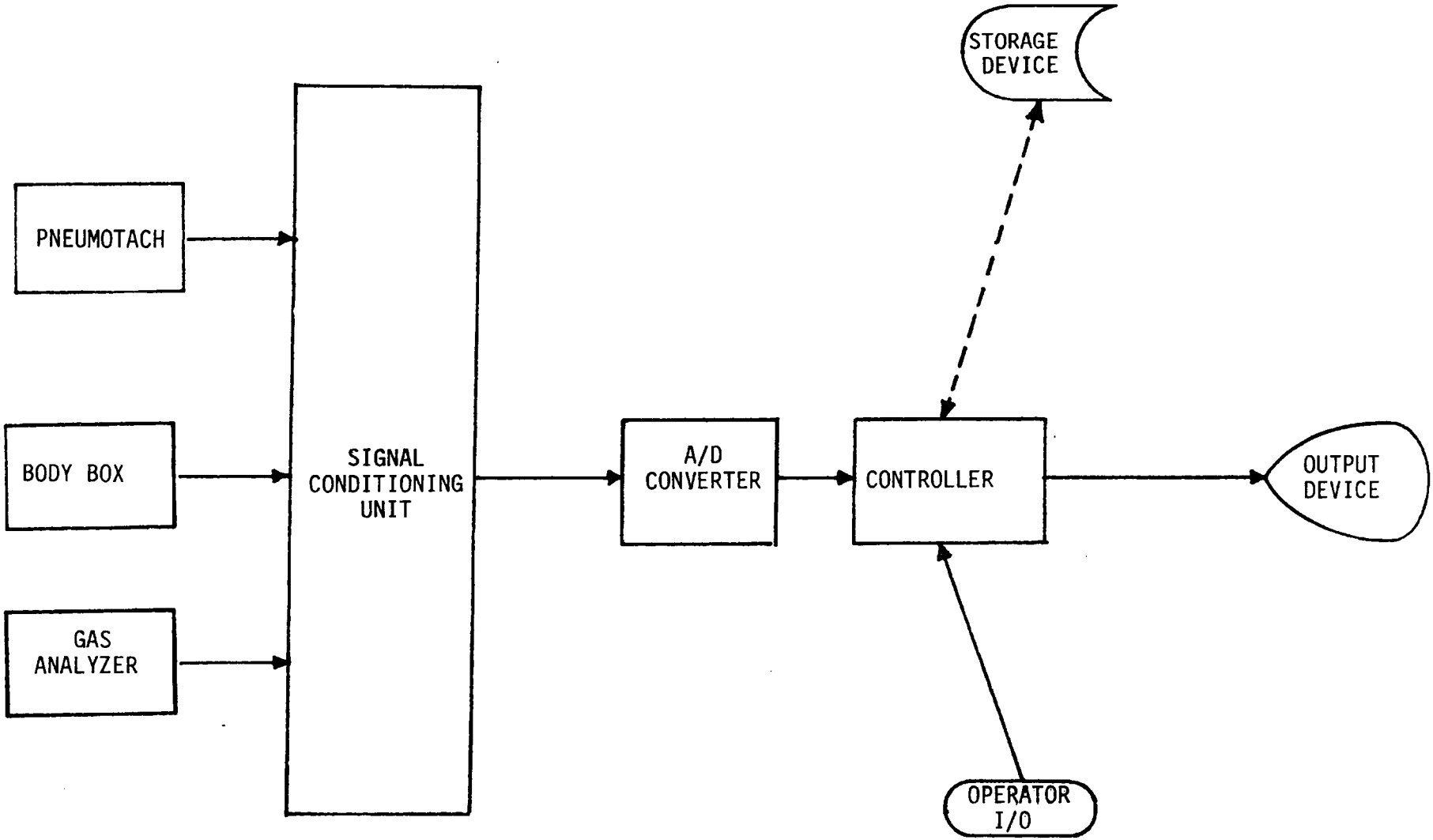
Blood gas determination

- new, committee being formed.

A.A.M.I.

Pulmonary Function Subcommittee

Spirometer - new, under preparation, to be completed in 1977.



PULMONARY FUNCTION TESTING SYSTEM - FUNCTIONAL REQUIREMENTS

CHAPTER III

TEST PROCEDURES AND MEASURED PARAMETER

Selection of parameters to be measured and calculated by the system were based on the survey of users (Appendix C) and of established products now being used in pulmonary function labs (Appendix D). Some of the parameters have been repeated either because there is some controversy regarding the best way to calculate certain parameters or because it is usual practice to calculate certain parameters by two different ways so that they can be compared. It should also be pointed out that while the nitrogen washout test and the helium dilution test are both established test procedures, they are seldom carried out together in the same lab. On the other hand, flow-volume loop procedure is gaining rapid acceptance, while the Spirometry test (especially Forced Expiratory) is the most common procedure utilized by almost every lab. This is mostly due to the fact that this procedure is easy to conduct and needs very simple equipment. The diffusing capacity test procedure is cumbersome and thus it finds limited use. Body Plethysmography procedure has limited use due to the need for complex calibration procedure and additional equipment not needed elsewhere. The blood gas analysis is rather widespread in use. Usually it is done with off-line instruments using a blood sample from the subject.

Several of the test parameters listed required predicted normal value calculations. These calculations are made on the basis of equations listed in Appendix A.

MODULE A-1 Spirometry - Vital Capacity

Instruments: Pneumotachometer; Mass Spectrometer

Gases Required: Calibration gases.

SL. No.	Parameters (Units)	Abb.+	Expressed In	Typical Value*	Primary/ Derived	Method of Calculation	Fig.
	Ventilation:						
1	Tidal Volume (mL.)	TV/V_T	BTPS	500 mL.	Primary	From Spirogram	1
2	Respiration Rate (per min) (max. variation: 5 - 70)	f		12-15/min	Primary	From Spirogram	1
3	Minute Volume	MV	BTPS	6000 mL/min	Derived	MV = (TV X f)	
	Lung Volumes:						
4	Expiratory Reserve Vol. (mL)	ERV	BTPS	1200 mL	Primary	From Spirogram	1
5	Inspiratory Capacity (mL)	IC	BTPS	3600 mL	Primary	From Spirogram	1
6	Inspiratory Reserve Vol. (mL)	IRV	BTPS	3000 mL	Derived	(IC - ERV)	1
7	Vital Capacity (L.)	VC	BTPS	4.8 L	Derived	(IC + ERV)	1

* The typical values are for healthy young males.

+ All abbreviations follow the pulmonary nomenclature report of ACCP-ATS Joint Committee, May 75. (1)

SPIROMETRY MODULE A-1

Vital Capacity: (Ventilation and lung volumes)

The subject breathes into the pneumotachometer for at least 1 minute. The number of breaths in 1 minute gives the respiration rate (f) and the tidal volume is given by

$$V_T = \frac{\text{Vol. expired (or inspired) over given period}}{\text{No. of breaths for same period}}$$

The volume is obtained by integrating the instantaneous flow rates.

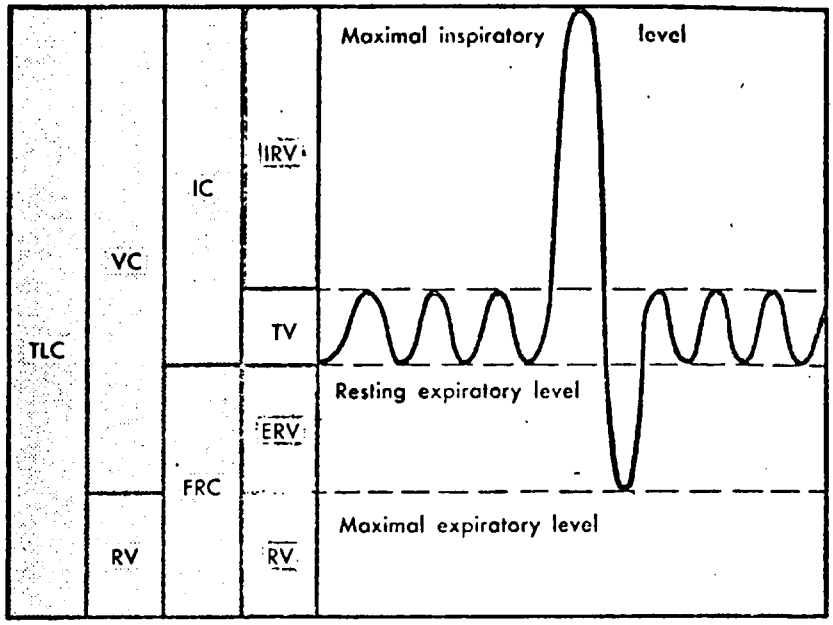
Minute volume is calculated as $MV = V_T \times f$.

The mass spectrometer samples the gas concentrations to generate correction factors for the flow rates as discussed under pneumotachometer specifications in Appendix B.

After normal breathing for 1 minute, the subject inhales maximally and then exhales maximally. IC is the volume inhaled from the resting expiratory level, established during the tidal volume calculation. ERV is the volume exhaled from the resting expiratory level. This is repeated twice and the average of the two IC and ERV values are calculated. Now IRV and VC can be derived from

$$IRV = (IC - ERV),$$

and $$VC = (IC + ERV) .$$



Lung volumes and capacities. Diagrammatic representation of various lung compartments, based on a typical spirogram. TLC, Total lung capacity; VC, vital capacity; IC, inspiratory capacity; TV, tidal volume; IRV, inspiratory reserve volume; ERV, expiratory reserve volume. Shaded areas indicate relationships between the subdivisions and relative sizes as compared to the total lung capacity (TLC).

FIGURE 1

MODULE A-2 Spirometry - Forced Expiratory Vital Capacity

Instrument(s): Pneumotachometer; Mass Spectrometer.

8	Forced Expir. Vital Capacity (L.)	FEVC	BTPS	4.8 L	Primary	From FVC Graph	2
9	Forced Expir. Volume upto time t (seconds) (L.)	FEVt	BTPS	4.0 L for t = 1 s.	Derived	Calculated for t = 0.5, 1.0, 3.0 seconds from FVC Curve	3
10	FEVt/FVC %	FEVt%	BPTS	83% for t = 1 sec.	Derived	Calculated	
11	Peak Expiratory Flow (L./min)	PEF	BTPS	400 L./min	Derived	From FVC Curve	4
12	Max. Mid Expiratory Flow Between 25% and 75% of Flow (L./min)	FEF 25-75%	BTPS	280 L./min	Derived	From FVC Curve	5
13	Forced Expiratory Flow between 200 & 1200 mL. of Vol.(L./min)	FEF 200-1200	BTPS	360 L./min	Derived	From FVC Curve	6

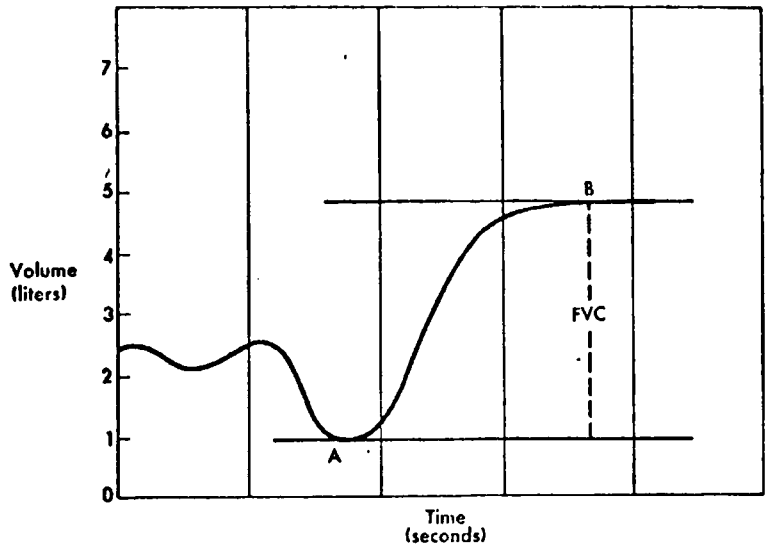
SPIROMETRY MODULE A-2

Forced Expiratory Vital Capacity

The Forced Vital Capacity is measured by having the subject expire as forcefully and rapidly as possible into a pneumotachometer after maximal inspiration. The volume is obtained by integrating the flow rates and must be corrected to BTPS. The volume is plotted against time in seconds. The time t = 0 is the point at which the flow rate exceeds +200 mL./second (figure 2) (this figure should be operator adjustable through the keyboard).

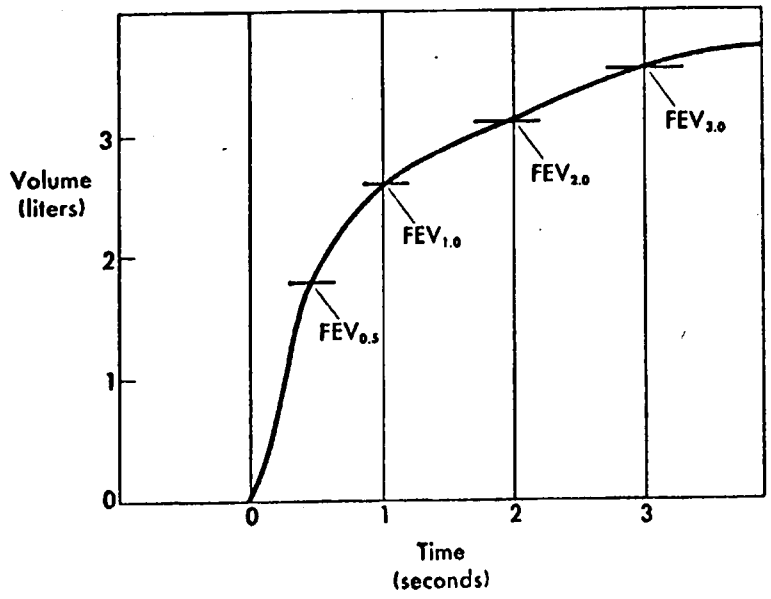
FEVt, PEF, FEF 25-75% and FEF 200-1200 are obtained from the FVC curve as shown in figures 3, 4, 5 and 6 respectively. All of them are corrected to BTPS.

The mass spectrometer is used in the same way as it was used in Module A-1, to generate correction factors for the flow rates.



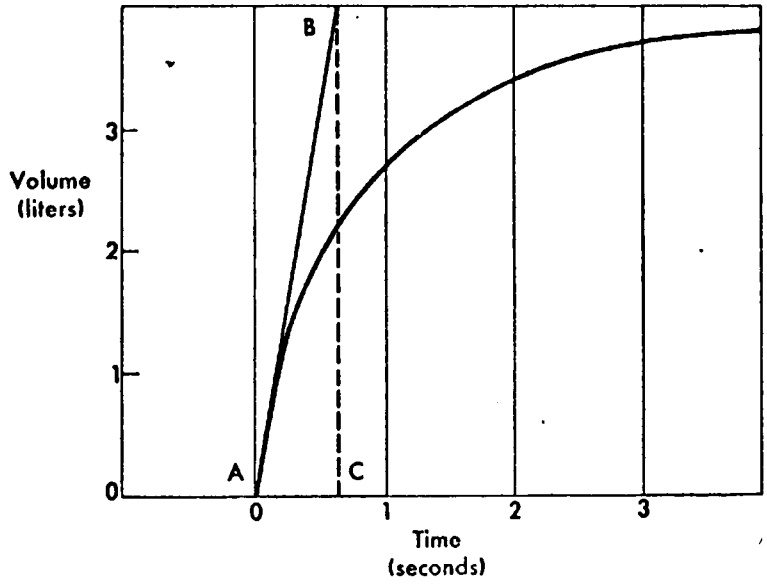
Forced vital capacity. Typical spirogram plotting exhaled volume against time. The subject expires as rapidly and forcefully as possible from maximal inspiratory level (A) to maximal expiratory level (B). At point x, flow rate is 200mL/sec.

FIGURE 2



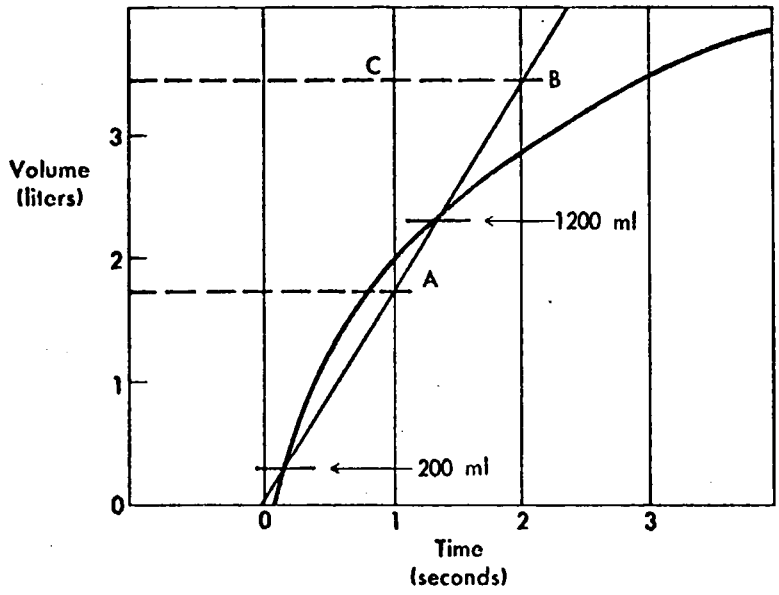
Forced expiratory volume maneuver. Spirogram of an FEV_T maneuver, with the subject exhaling as forcefully and rapidly as possible. Marks indicate the FEV at the various intervals.

FIGURE 3



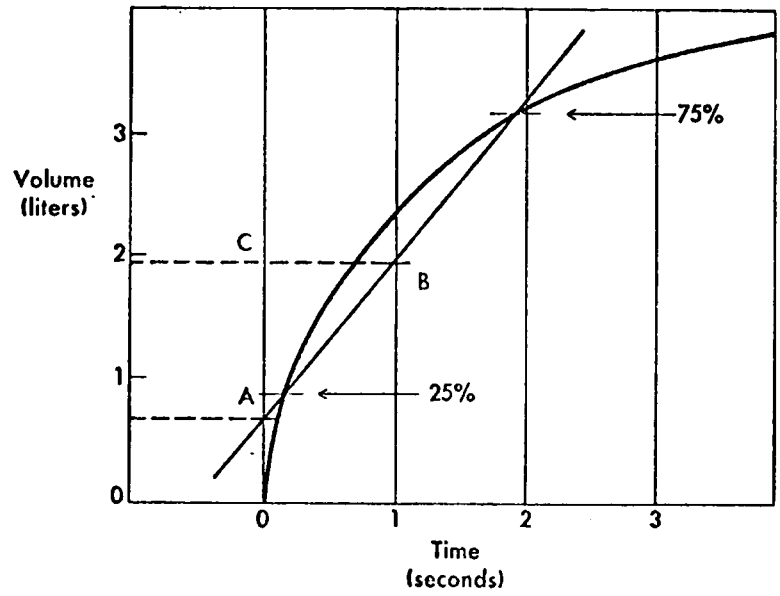
Peak flow tangent. FEV spirogram which has a line drawn tangent to the steepest part of the curve, line AB. In this case the tangent has a slope such that it does not intersect the two closest time lines, 1 second apart. The flow rate can be computed by dividing the volume (BC) by the time interval (AC).

FIGURE 4



$FEF_{25\%-75\%}$. An FEV spirogram which has the 25% and 75% points marked; these points are determined by multiplying the FVC by 0.25 and 0.75. A line connecting these points is extended to intersect two time lines 1 second apart, points A and B. The flow rate is the vertical distance between the points of intersection (AC).

FIGURE 5



$FEF_{200-1200}$. An FEV spirogram on which the 200 and 1200 ml points of the expiration have been marked; a line connecting these two points is extended to cross two time lines 1 second apart, points A and B. The flow rate can be read as the vertical distance between the points of intersection (AC).

FIGURE 6

MODULE A-3 Spirometry - Forced Inspiratory Vital Capacity

Instrument(s): Pneumotachometer.

14	Forced Inspiratory Vital Capacity (L.)	FIVC	BTPS	4.8 L	Primary	From FVC Curve
15	Max. Inspiratory Flow (L./min)	PIF	BTPS	400 L./min	Derived	From FVC Curve
16	Max. Voluntary Ventilation at X breaths/min. (L./min)	MVV_X	BTPS	130-200 L./min	Primary	Voluntary ventilation for 10 second test period at a respiration rate of 12. Must monitor respiration rate during this maneuver.

SPIROMETRY MODULE A-3

Forced Inspiratory Vital Capacity

The FIVC is measured exactly the same way as the FEVC except now the subject inspires as forcefully and rapidly as possible through a pneumotachometer after maximal expiration.

The maximum voluntary ventilation is measured by having the subject breathe deeply while maintaining a respiration rate of 12 ± 1 breaths/min. Data is collected for 10 seconds after the subject has reached the steady respiration rate. The expired (or inspired) volume can be obtained by integrating the flow rates and must be corrected to BTPS. The respiration rate must be displayed on the display screen as a visual feedback to the subject.

Instrument(s): Pneumotachometer

17.	Flow-Volume Loop		BTPS		Primary	Flow and volume information for a forced inspiration followed by forced expiration maneuver.	7
(a)	Forced Vital Capacity (L.)	FVC	BTPS	4.8 L.	Derived	From loop	
(b)	Peak Inspiratory Flow (L./min)	PIF	BTPS	400 L./min	Derived	From loop	
(c)	Peak Expiratory Flow (L./min)	PEF	BTPS	400 L./min	Derived	From loop	
(d)	Forced Exp. Flow at 50% Flow (L./min)	FEF 50%	BTPS		Derived	From loop	
(e)	Forced Insp. Flow at 50% Flow (L./min)	FIF 50%	BTPS		Derived	From loop	

SPIROMETRY MODULE A-4

Flow-Volume Loop:

The flow-volume loop is a test of ventilatory function in which the velocity of airflow is plotted against volume during a maximal expiratory and inspiratory maneuver by the subject (figure 7).

The following parameters can be calculated from a flow-volume loop:

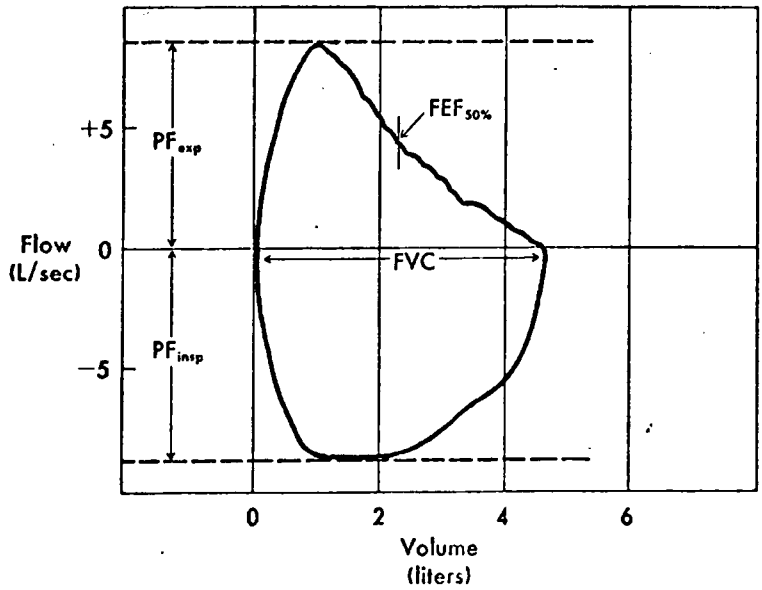
(i) Forced Vital Capacity

(ii) Peak Inspiratory Flow

(iii) Peak Expiratory Flow

(iv) FEF 50%

(v) FIF 50%



Flow-volume loop. Flow-volume spirogram in which an FEV and an FIV maneuver are recorded in succession. Flow rate is plotted on the vertical axis and volume on the horizontal axis. Peak flows for inspiration and expiration can be read directly, as can the FVC. The instantaneous flow rate at a particular point in the FVC can be measured directly.

FIGURE 7

MODULE A-5 (a) Single breath N_2 washout

Instrument(s): Pneumotachometer; Mass Spectrometer

Gases Needed: Calibration N_2; pure O_2 source

Info Required: Respiration rate and tidal volume from A-1.

This test cannot be completed before the pirometry (Vital Capacity) test has been performed.

18	Anatomic Dead Space (mL.)	VDAN	BTPS	150 mL.	Primary	From % N_2 & Volume Plot.	8
19	Nitrogen Distribution (% N_2)	DELTAN2	BTPS	< 1.5% N_2	Primary	Change in N_2 conc. in 500 mL. of exhaled gas after 750 mL. is expired; inspired gas is 100% O_2.	
20	Closing Volume (mL.)	CV	BTPS		Primary	From % N_2 vs. Volume plot.	
21	Alveolar Ventilation (L/min)	'VA	BTPS	4.2 L/min	Derived	'VA = f (V_T - VDAN)	

N_2 WASHOUT MODULE A-5 (a)

Single Breath Nitrogen Washout

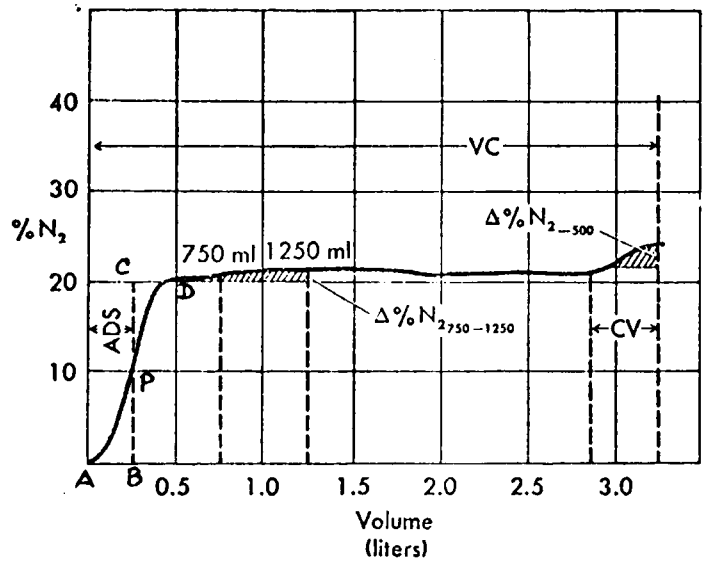
This test measures the increase in the concentration of N_2 in the 500 ml. of gas exhaled after the first 750 ml. of a single breath of 100% oxygen. The subject inhales a single breath of pure O_2 and then expires slowly into a pneumotachometer with the mass spectrometer, which rapidly monitors the N_2 concentration of the expired gas. The expired volume is measured by the pnemotachometer. These two parameters are plotted against each other on a spirogram. During the first part of the breath O_2 is exhaled, and the N_2 concentration remains zero until a volume equal to the anatomic dead space has been exhaled. Then the N_2 concentration rises rapidly to the level of alveolar N_2 diluted with O_2. Since alveolar gas mixes with dead space gas during exhalation, the curve depicting the change in N_2 concentration does not present a "square front". By numerical methods, a square front can be constructed and the anatomic dead space is the volume expired up to the square front.

The change in the nitrogen concentration over the 750 and 1250 ml. interval is called the nitrogen delta (ΔN_2) and usually is pure alveolar gas. Increases from normal values of ΔN_2 are found in diseases characterized by uneven gas distribution during inspiration and unequal emptying flow rates during expiration.

The closing volume is the volume expired after the abrupt upslope in N_2% until the FVC is reached.

The alveolar ventilation can be now calculated as

$$\dot{V}_A = \text{Respiration Rate X (Tidal Volume - Anatomic Dead Space)}$$



Single-breath nitrogen elimination. Plot of the rise in nitrogen concentration on expiration after a single breath of 100% O_2. The elimination curve can be divided into four parts. The first is the extreme beginning of the expiration when pure oxygen is being exhaled; second comes an abrupt rise in N_2 concentration as mixed bronchial and alveolar air are expired; the third stage includes a plateau in expired nitrogen concentration, due mostly to alveolar gas; last is a somewhat noticeable rise at the very end of the breath due to the closure of some airways before others. The anatomic dead space can be estimated from the second stage of the expiration. The ΔN_2 over the 750 to 1250 ml interval can be read directly. The closing volume, which indicates small airway closure, is read as the volume from the point of noticeable increase in N_2 concentration to the end of the breath.

FIGURE 8

MODULE A-5(b) Multiple Breath N_2 Washout

Instrument(s): Pneumotachometer; Mass Spectrometer

Gases Required: 100% O_2 source, N_2 calibration gas.

Info Required: IC, ERV, respiration rate data from Module A-1 and VDAN value from Module A-5 (a).

This test cannot be completed before the Spirometry (Vital Capacity) and Single Breath N_2 Washout Test has been completed.

22	Functional Residual Cap. (mL.)	FRC	BTPS	2400 mL.	Primary	Open ckt. method $FRC = \frac{\%\ N_2\ final\ X\ Exp.\ Vol}{\%\ N_2\ atmospheric}$	
23	Residual Volume (mL.)	RV	BTPS	1200 mL.	Derived	RV = (FRC - ERV)	
24	Total Lung Capacity (mL.)	TLC	BTPS	6000 mL.	Derived	TLC = (FRC + IC)	
25	RV/TLC %			20-23%	Derived	(RV/TLC) X 100	
26	Inspired Gas Distribution Index	IDI		1.8 ±0.2	Derived	IDI = V_A/FRC X (K) where K = natural log of 72.	9

N_2 WASHOUT TEST MODULE A-5 (b)

Multiple Breath N_2 Washout

This nitrogen washout test measures the concentration of N_2 in alveolar gas over a period of 7 minutes of 100% O_2 breathing, and washing all the N_2 out of his lung.

Suppose that the lung volume is V_1 and that its concentration of N_2 in the lung before washout is χ% and assuming no net change in N_2, the following is true:

$$V_1 \cdot \chi = (V_1 + V_2)\ C_2$$

$$V_1 = \frac{V_2\ C_2}{(\chi - C_2)} = FRC$$

The index of distribution of inspired gas is defined as (figure 9):

$$IDI = \frac{V_A\ (tot)}{FRC\ X\ K}$$

where K = Constant such that an ideal lung will have an IDI equal to 1.00, and is equal to the natural log of 72, and $V_A\ (tot) = V_{tot} - f\ (V_D)$

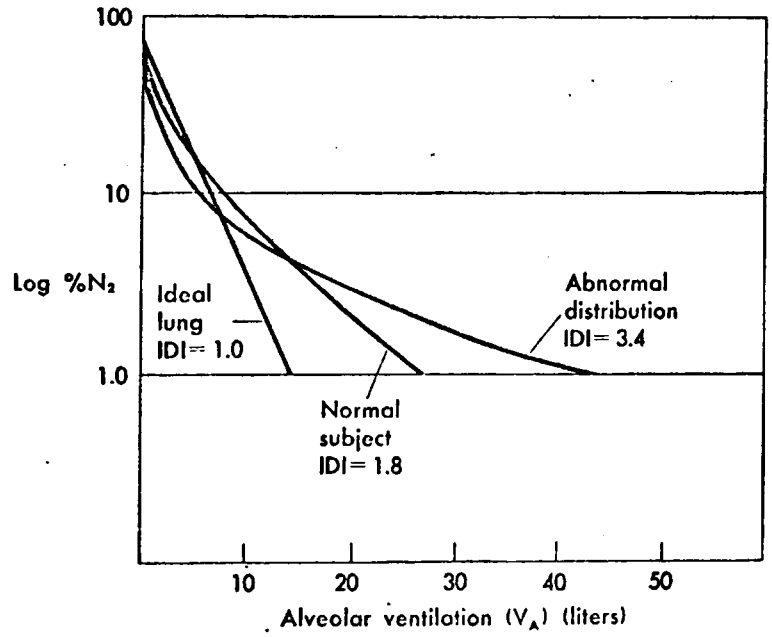
= (Total volume expired during test) - no. of breaths X (respiratory dead space)

Respiratory dead space was assumed equal to the anatomic dead space.

The residual volume and total lung capacity can be calculated from:

$$RV = (FRC - ERV)$$

and $$TLC = (FRC + IC)$$



Inspired gas distribution index (IDI). Illustrated is a plot of the logarithm of N_2 concentration versus the alveolar ventiliation. The IDI is derived thus:

$$IDI = \frac{V_A}{FRC\ (K)}$$

where

K = Constant equal to the natural log of 72

By definition, IDI for an ideal, single-chambered lung is 1.0. Plotting log N_2 concentration again alveolar ventiliation instead of total expired volume eliminates dependence on rate, tidal volume, and dead space as determinants of the shape of the washout curve and allows a quantitative measurement of the evenness of distribution.

FIGURE 9

MODULE A-6 Helium Dilution (Closed Circuit Method)

Instrument(s): Mass Spectrometer; Gas Chamber w/CO_2 Absorber; Stop Valve on Pneumotachometer; Two Way Solenoid Valve on Gas Sampling Line. (Figure 11)

Gases Required: O_2 - N_2 Mixture, Helium.

Info Required: Value of ERV and IC from Module A1.

This test cannot be performed until the Vital Capacity (Spirometry) test has been completed.

27	Functional Residual Cap. (mL.)	FRC	BTPS	2400 mL.	Primary	$FRC = \frac{(\%\ He_{initial} - \%\ He_{final})}{\%\ He_{final}} \times$ Initial Vol	10
28	Residual Volume (mL.)	RV	BTPS	1200 mL.	Derived	RV = (FRC - ERV)	
29	Total Lung Capacity (mL.)	TLC	BTPS	6000 mL.	Derived	TLC = (FRC + IC)	
30	RV/TLC %			20-23%	Derived	(RV/TLC) X 100	

HELIUM DILUTION TEST MODULE A-6

Closed Circuit Method:

The functional residual capacity can be calculated indirectly by diluting the gas in the lungs with a gas of known concentration. A suitable chamber with a CO_2 absorber is filled with a known volume of gas (2.5 liters) to which a known volume of helium (≈10%) is added. The initial concentration of He is recorded and the subject is connected to the chamber. The subject rebreathes the gas in the chamber until the concentration of the helium falls to a stable level (He concentration changes less than 0.05% between two successive samples) usually in less than 7 mins. The final concentration of helium is then recorded.

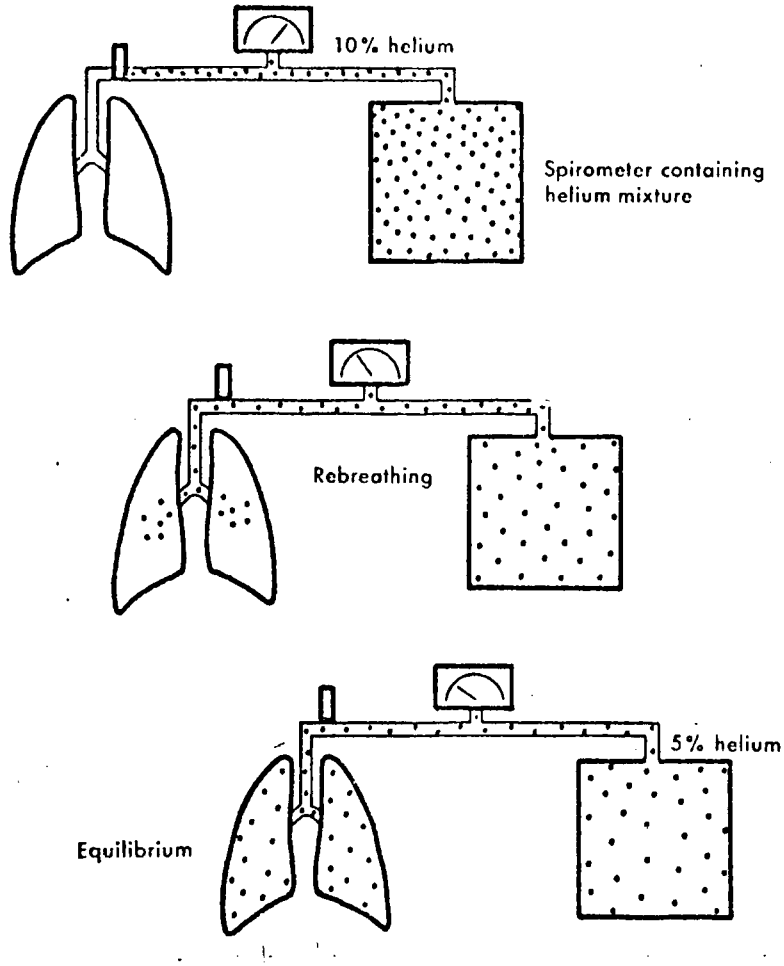
$$\text{Initial volume of gas in chamber} = \frac{\text{He added (mL.)}}{\%\ \text{He initial}}$$

$$\text{FRC} = \frac{(\%\ \text{He}_{\text{initial}} - \%\ \text{He}_{\text{final}})}{\%\ \text{He}_{\text{final}}} \times \text{initial volume of gas}$$

FRC must be converted to BTPS.

Again, RV = FRC - ERV

and TLC = (FRC + IC)



Closed-circuit determination of residual volume. The lungs of a subject breathing air contain no helium. The subject then rebreathes a mixture of He and air or O_2, whose volume and He% are known. Helium is diluted until an equilibrium is reached. The volume of He initially present is known from the initial concentration and the volume of the rebreathing system. At the end of the test the same volume of He is now diluted in a larger volume (rebreathing system + lungs), and the total volume is computed from the initial He volume and the final He concentration:

$$\frac{V_{He\ initial}}{\%_{He\ final}} = \text{Total volume of system}$$

The switch from air to the He mixture must be made at the end-expiratory level for accurate measurement of FRC.

FIGURE 10

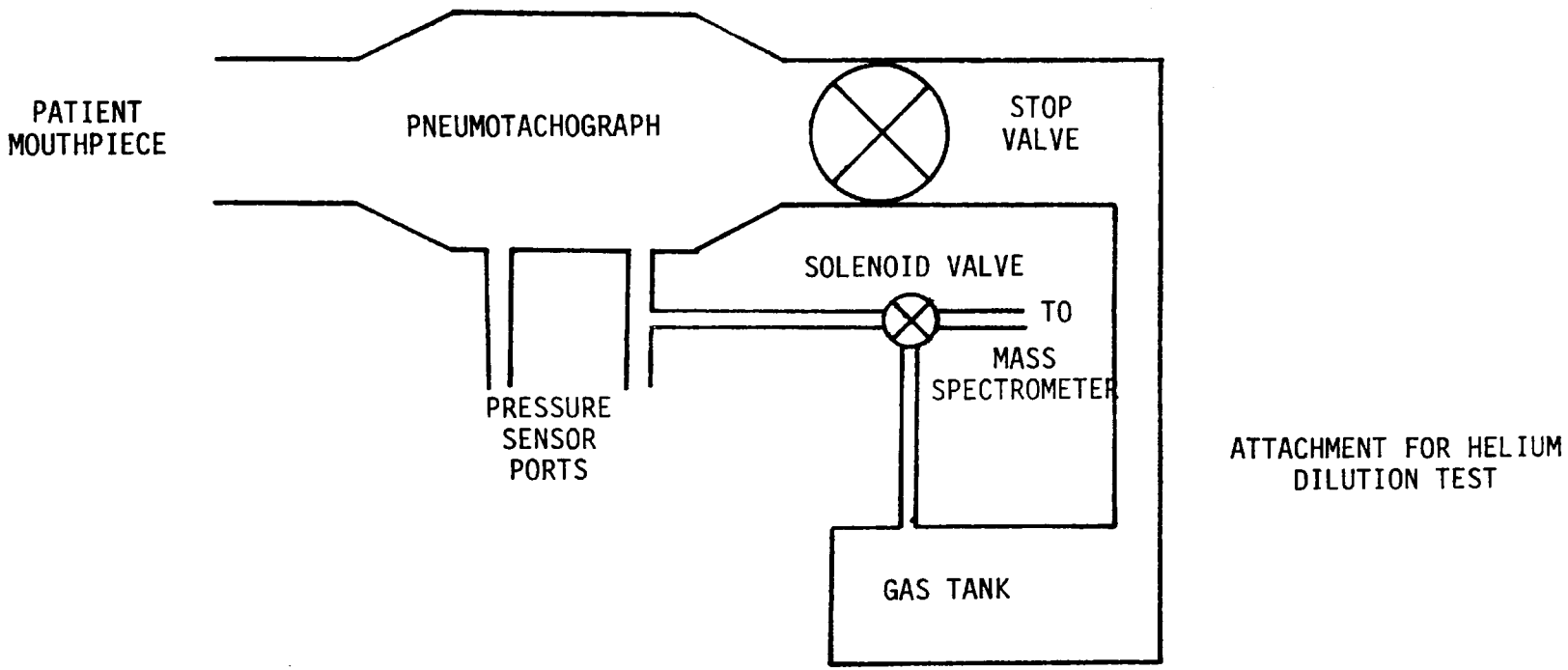


FIGURE 11

PNEUMOTACHOMETER SUBSYSTEM FOR HELIUM DILUTION TEST

Instrument(s): Pneumotachometer; Mass Spectrometer; gas chamber; stop valve

Gases Required: CO and He sources w/gas mixer

Info. Required: VDAN from Module A-5 (a).

31	Single breath CO diffusing capacity (mL./min/mmHg)	SBDLCO	STPD	20 mL. CO/ min/mmHg	Primary	Subject breathes 0.3% CO + 10% He deeply and holds for 10 seconds. $DLCO = \frac{\text{mL. CO transferred/min}}{\text{Mean } P_{A_{CO}} - \text{Mean Capillary } P_{CO}}$ $= \frac{VA}{(PB-47)(t_2-t_1)} \times \log \frac{F_{ACO}t_1}{F_{ACO}t_2}$ where $FACOt_1$, $FACOt_2$ are the fractions of CO in alveolar gas before and at the end of diffusion, $(t_2 - t_1)$ is usually 10 secs.
32	Steady State CO diffusing capacity (mL. CO/min./mmHg)	SSDLCO	STPD		Primary	Subject rebreathes rapidly from a tank containing a 0.3% CO gas mixture.

DIFFUSING CAPACITY MODULE A-7

Single Breath Diffusion Test: (for diffusion capacity calc.)

The test subject inspires a deep breath of a gas mixture containing 0.3% CO and 10% He and holds his breath for 10 seconds. The milliliters of CO transferred is the difference in concentrations of CO in alveolar gas at the beginning and end of the 10 second interval. The DLCO is calculated as:

$$DLCO = \frac{V_A}{(P_B \cdot 47)(t_2 - t_1)} \times \log \frac{(F_{ACOt1})}{(F_{ACOt2})}$$

where

V_A = alveolar ventilation

P_B = barometric pressure

$(t_2 - t_1)$ = interval (10 sec.)

F_{ACOt1} = Fraction of CO in alveolar gas before diffusion

and F_{ACOt2} = Fraction of CO in alveolar gas at end of diffusion.

F_{ACOt_1} is computed by multiplying the initial CO concentration (0.3%) by $\frac{\text{Inspired He concentration}}{\text{Expired He concentration}}$

A closed breathing system, capable of monitoring both CO and He concentrations continuously, is necessary for this test.

Steady State Diffusion Test

The subject rebreathes from a reservoir tank containing 0.3% CO at a rapid rate for 30 seconds. Gas samples are analyzed by the mass spectrometer after 10 and 30 seconds for CO concentration. The total volume of the tank/lung system multiplied by the change in CO concentration, determines the volume of CO transferred. The mean capillary P_{CO} is considered to be zero and the mean alveolar P_{CO} is calculated from the CO concentration in the tank at the beginning and end of the test interval.

MODULE B Body Plethysmography

Instrument(s): Body box with mouth and plethysmograph pressure transducers and pneumotacho-meter, shutter valve assembly under processor control, small display screen, calibration equipment.

33	Thoracic Gas Volume (mL.)	TGV	BTPS	2400 mL.	Primary	$V = (P^1V^1)/P$ where P^1,V^1 and P are new alveolar pressure, new thoracic volume and original alveolar pressure	1
34	Airway Resistance (cm H_2O/L./sec.)	RAW	BTPS	1.6 cm/H_2O/ L./sec.	Primary	$RAW = \Delta P/\Delta V = \frac{(Patmosp. - Pmouth)}{Flow\ Rate}$	1
35	Airway Conductance (L./sec./cm. H_2O)	GAW	BTPS	.625L/sec/ cm H_2O	Derived	GAW = 1/RAW	

BODY PLETHYSMOGRAPHY MODULE B

The thoracic gas volume is calculated with the body plethysmography setup. The critical assumption here is that the mouth pressure equals alveolar pressure when there is no airflow such as the end expiration point of the respiratory cycle. The subject breathes normally through the pneumotachometer and when the end expiration point is reached, an electric shutter closes the mouthpiece so that the thoracic volume increases on inspiration, and consequently the thoracic gas is decompressed. Since little or no airflow occurs, the pressure measured in the patient's airway is assumed to be equal to the alveolar pressure. The change in thoracic volume is determined by noting the increase in pressure in the body box. By applying Boyle's Law:

$$PV = P^1V^1$$

where P, P^1 are the original and new alveolar pressures, and V, V^1 are the original and new thoracic volumes.

Assuming constant temperature, we get:

$$V = \frac{P1V1}{P}$$

For this measurement, the processor must monitor the respiration cycle, recognize the end expiration point and send a control signal to close the shutter in the pneumotachometer assembly.

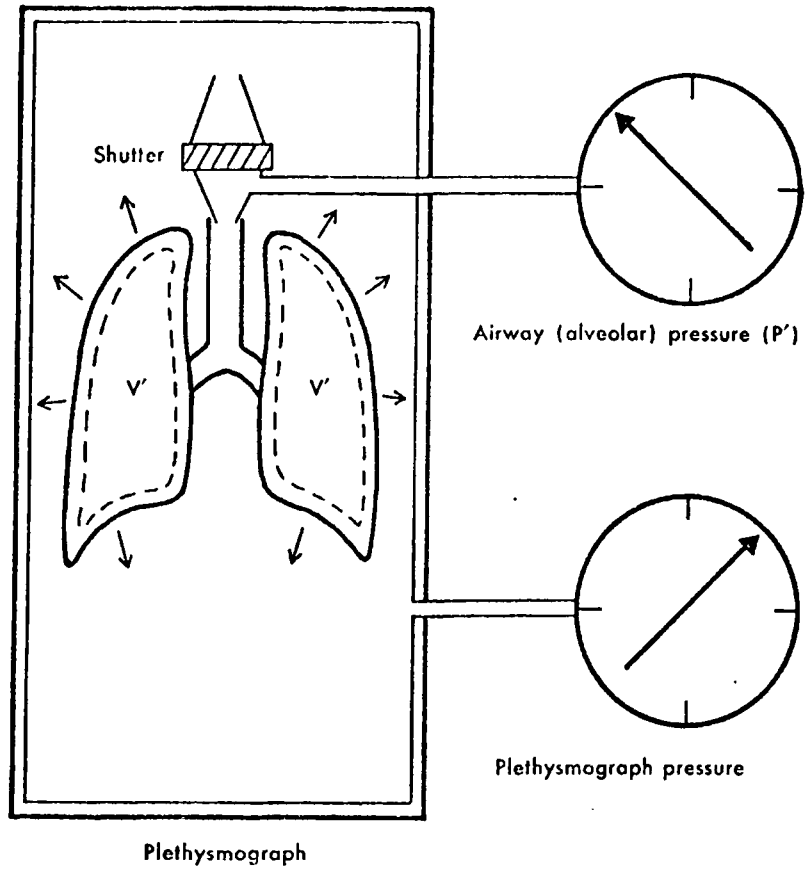
Airway resistance can only be measured during the time when gas is flowing into or out of the lung. The measurements of atmospheric and alveolar pressures are required to determine the pressure difference responsible for gas flow. This maneuver is usually done with the patient

taking fast shallow breaths (panting), because the airway resistance decreases with deep breathing. When the subject inspires, alveolar pressure falls and the alveolar gas occupies a greater volume. The displacement volume is measured by a pressure sensor as a pressure increase in the body box; therefore the alveolar pressure can be calculated from the associated pressure changes. The flow rates are measured by the pneumotachometer.

Therefore

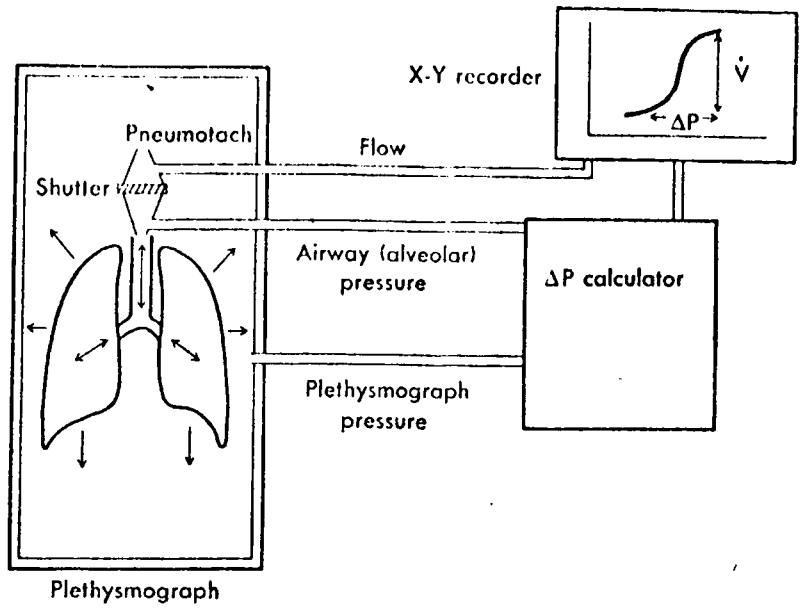
$$\text{Airflow resistance (RAW)} = \frac{\text{Atmospheric pressure - alveolar press}}{\text{Flow}}$$

The RAW is a function of the rate of panting. Therefore the measurements must be made at a constant rate. In order to achieve this, the subject should have a visual feedback of his rate of panting.



Thoracic gas volume. The body plethysmograph is used to measure the thoracic gas volume. Boyle's law states that volume varies inversely with pressure if the temperature is held constant: $PV = P'V'$. The plethysmograph with manometers for measurement of chamber pressure and airway pressure is illustrated. An electronic shutter momentarily occludes the airway so that airway pressure is approximately equal to alveolar pressure. Simultaneously, the alveolar gas is decompressed because of enlargement of the thorax. This change is reflected by an increase in chamber pressure, and an estimation of the volume change can be derived. When the original pressure (P), the new pressure (P'), and the new volume (V') are known, the original volume (thoracic gas volume) can be computed directly from Boyle's law.

FIGURE 12



Measurement of airway resistance. Diagrammatic representation of the measurement of airway resistance by the body plethysmograph method:

$$\text{Airway resistance} = \frac{\text{Atmospheric pressure - Alveolar pressure}}{\text{Flow}}$$

Flor (V) is measured directly by means of the pneumotach. The pressure differential between the chamberand the alveoli is measured thus: plethysmograph pressure is monitored by means of a sensitive manometer in the chamber; alveolar pressure is measured as airway pressure during intervals when no gas flow is occurring. A shutter occludes the airway momentarily, usually at end-expiration, and a manometer monitors the falling pressure. The pressure differential is calculated and delivered to an appropriate display device.

FIGURE 13

MODULE C Blood Gas Analysis

Instrument(s): Mass Spectrometer; Gas diffusion membrane catheter.

Info Required: Fractional conc. of inspired oxygen.

36.	Arterial Oxygen Tension (mmHg)	P_{aO_2}	95 mmHg	Primary	Arterial insertion of silastic membrane catheter is required.
37.	Arterial Carbon Dioxide	P_{aCO_2}	40 mmHg	Primary	Arterial insertion of silastic membrane catheter is required.
38.	Percentage Physiologic Shunt (%)	$\dot{Q}_{SP}$	less than 7%	Derived	$\frac{\dot{Q}_{SP}}{\dot{Q}_T} \times 100 = \frac{(P_{AO_2} - P_{aO_2}) \times .0031 \times 100}{4.5 + (P_{AO_2} - P_{aO_2}) \times .0031}$
39.	Alveolar Oxygen Tension (mmHg)	P_{AO_2}		Derived	$P_{AO_2} = F_{IO_2} \times (\text{Baro. Press} - 47) - \frac{P_{aCO_2}}{RQ}$ where F_{IO_2} = fractional conc. of inspired O_2, and RQ = respiration exchange rate assumed equal to 0.8.

BLOOD GAS ANALYSIS MODULE C

Both the P_{aO_2} and P_{aCO_2} can be measured by inserting a gas diffusing silastic membrane catheter into the radial or brachial artery for 10 seconds.

To calculate the value of physiological shunt, the subject is allowed to breathe 100% oxygen for at least 20 minutes at atmospheric pressure so that all the N_2 is washed out of the lungs and the hemoglobin is completely saturated.

$$\text{Now } {}'Q_{SP} = \frac{(P_{AO_2} - P_{aO_2}) \times .0031}{4.5 + (P_{AO_2} - P_{a.O_2}) \times 0.0031}$$

where ${}'Q_{SP}/{}'Q_t$ = Ratio of shunted blood to total profusion

P_{AO_2} = Alveolar O_2 tension

$$= F_{IO_2} \times (\text{Baro. pressure} - 47) - \frac{P_{aCO_2}}{RQ}$$

where F_{IO_2} = Fractional conc. of inspired O_2

and RQ = Respiratory exchange rate $\simeq 0.8$,

SYSTEM CALIBRATION PROCEDURE

Three instruments in the system have to be calibrated:

(i) The pneumotachometer will be calibrated once a day under processor control for the following gas mixtures and rates:

(a) 80% N_2 and 20% O_2 at flow rates of -600 mL./sec, -2400 mL/sec and -6000 mL./sec.

(b) 76% N_2, 18% N_2 and 6% CO_2 at flow rates of +600 mL./sec, +2400 mL./sec and +6000 mL./sec.

Messages on the display screen will direct the operator as to the steps he has to follow.

(ii) The mass spectrometer will be calibrated under processor control for the above two gas mixtures concurrently with the pneumotachometer. In addition it will be calibrated once a day for the two following gas mixtures at any suitable rate (at, say, +2400 mL./sec):

(a) 5% helium in 95% O_2 or N_2.

(b) 0.25% CO in 99.75% N_2.

Messages on the display screen will direct the operator as to the steps he has to follow.

It should be noted that the helium and carbon monoxide calibration will be required only when the optional helium dilution and carbon monoxide diffusion capacity tests are incorporated in the system.

(iii) The body plethysmograph will have its own calibration circuitry and methodology and will start under processor command.

The positive and negative flow rates indicated relate to the flows away from and towards the mouthpiece to simulate expiration and inspiration respectively.

CHAPTER IV
HARDWARE REQUIREMENTS

The PNEUMOTACHOMETER requirements have been discussed in Appendix B.

MASS SPECTROMETER:

The mass spectrometer should be the only respiratory gas analyzer in the system replacing the four or five separate gas analyzers now used for the various tests in the pulmonary function laboratories. It must also analyze blood gases collected through a silastic gas diffusion membrane catheter and must monitor gas samples from the pneumotachometer for 30 seconds at the beginning of the Spirometry, Helium Dilution, Nitrogen Washout and Diffusing Capacity tests to provide correction factors for the calibration data.

The mass spectrometer should be a four channel programmable instrument capable of analyzing upto four gases simultaneously. In order to make the instrument a stand alone product, so that it can be used in other application areas, it should contain all the signal conditioning circuitry required. Therefore there should be no separate signal conditioning module in the system mainframe for gas analyses.

Calibration should be required only once a day. It should be noted here, that to date mass spectrometers have found limited application due to its high initial cost and because of skill required for their maintenance and operation.

SIGNAL CONDITIONING REQUIREMENTS

In mass spectrometry, the various molecular species in a gas mixture are separated according to their molecular weights, or, more accurately, according to the mass/charge ratios of their ions. The gas molecules are ionized inside the gas chamber by an electron beam, and the ions of the molecule and its component fragments are accelerated along the tube by an electrostatic field. The ions are then deflected into curved paths by a perpendicular magnetic field. The radius of curvature of the path of a given ion is directly proportional to its mass/charge ratio. Thus ions of different species are separated in space and, by suitable adjustment of the electrostatic and magnetic fields, the ions of single species may be focused on an ion collector, which measures the charge or current carried by the ions. In order to analyze the presence of, say, 4 gases in a mixture, the accelerating voltage can be switched back and forth to the four values in rapid succession.

The mass spectrometer signal conditioning unit must have:

(a) Ion collector output and amplifiers,

(b) Peak detection circuitry which will measure peak amplitudes of the signal at programmed mass numbers,

(c) Circuitry that will convert ion collector outputs to partial pressures of gases of interest,

and,(d) Circuitry that will control the number of sampling channels and the mass numbers these channels are searching for according to the following chart:

TEST	NO. OF CHANNELS	SEARCHING FOR
Spirometry	3	O_2, N_2, CO_2
Nitrogen Washout	1	N_2
Helium Dilution	1	He
Diffusing Capacity	2	He, CO
Blood Gas	2	O_2, CO_2

FUNCTIONAL SPECIFICATIONS

Mass Range:	4 to 50 (expandable to 2-150)
	It is also important to minimize requirements for high technical skills in operation and maintenance.
No. of Channels:	4
Sampling Rate:	10 samples/second
Mass Discrimination:	$\geq$ 20
Sample Size:	$<$ 50 mL./minute
Accuracy:	Better than ±2%.
Output Voltage:	+10 volts
Response Time:	90% in or under 100 milliseconds
Sensitivity (min. det. conc.)	$\leq$ 0.1%
Operating Temp.:	5^{o} to $50^{o}C$
Storage Temp.:	-30^{o} to $+65^{o}C$
Humidity:	5% to 95% (non condensing)

The sampling line should be sufficiently long and flexible to make easy connection from the patient's mouthpiece to the instrument and should maintain a constant sample chamber pressure in face of changes in gas composition, viscosity, temperature and water vapor content. It is also important to minimize requirements for high technical skills in operation and maintenance.

BODY PLETHYSOMOGRAPH

The body plethysmograph system should have the following components:

(a) Body box - constant 6 liters volume
- hermetically sealed
- self sealing door.

(b) Pneumotachometer flow sensor (Appendix B).

(c) Mouth pressure sensor - with natural frequency of 600 Hz and range of ±100 cm H_2O.

(d) Box pressure sensor - with natural frequency of 600 Hz, and range of ±2 cm H_2O.

(e) Relay operated mouth piece shutter assembly.

(f) Patient feedback mechanism - a panel meter, a light indicator or one channel oscilloscope displaying respiration rate.

The actual configuration of the Body Plethysmography signal conditioning module cannot be determined until more is known about the selected body box. However it will have a signal amplification circuit and will control calibration for temperature compensation and automatic zeroing of the flow and pressure channels.

SPIROMETRY SIGNAL CONDITIONING MODULE

The spirometry module should supply excitation voltage to the pneumotachograph heating element and the pressure sensor, and will receive an analog signal proportional to the flow rates from the pressure sensor. A multiple range DC amplifier will be required to get suitable amplitude of the recorded waveform.

Transducer Excitation: +5 VDC for heating element
10 VDC for pressure sensor.

Max. Input Range: ±72 mV for ±720 L./minute flow rate
(Assumes use of silicon strain gage sensor - Appendix B)

Flow Output Range: ±10V

Amplification:

Module	Input Flow Rate	Output
A1	360 L./min	10V
2	720 L./min.	10V
3	720 L./min	10V
4	720 L./min	10V
5	72 L./min	10V
6	72 L./min	10V
7	72 L./min	10V

Calibration Points: ±1200 mL./sec (1V); ±2400 mL./sec (2V) and ±6000 mL./sec (5V).

Temperature: ±5^{o} to +50^{o}C, operating
-30^{o} to +65^{o}C, storage.

Humidity: 5% to 95% (non condensing).

DISPLAY UNIT REQUIREMENTS

The system requires a display unit capable of handling computer generated graphic/alphanumeric information. This system has no monitoring function and all the data is collected for short durations lasting from 10 seconds to 7.0 minutes. A worst case sample of the display screen appears in figure 14. The display should have an area of about 25 cm x 20 cm and should be able to display 26 rows of 48 characters. This helps display, in one page, the largest report required. The characters can be of single font size and upper case only. A particular frame of graphic and alphanumeric data should appear on the screen till the operator wants to remove it. The 63 character ASCII is adequate to represent all the characters that require to be displayed. 70% of the screen width will contain the graphic plot with a maximum of 400 display points for the plot with the remaining space available for grid lines and labels.

HARD COPY UNIT REQUIREMENT

The hard copy unit should be a slave to the display which prints out the complete frame appearing on the screen when the operator presses a print button on the function keyboard. It should therefore have a 63 ASCII character set, and should be able to print 26 rows of 48 characters on each page.

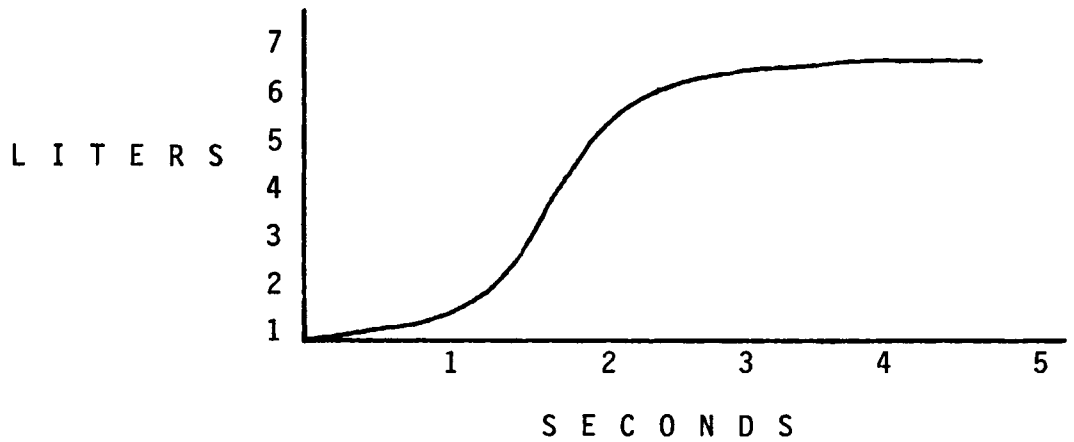
HONEYWELL CHARITY HOSPITAL 12-31-76 10:00

DOE, JOHN E. M 25YR. 128LBS. 56INCH

NO. XYZ123456 BRONCHIAL EMPHYSEMA

REF PHYSICIAN: TOM BROWN

SPIROMETRY TEST: FORCED EXP VITAL CAPACITY



	PRED	OBS	%PRE	PRED	OBS	%PRE
FEVC						
FEV1						
FEV1/FVC%						
FEV3						
FEV3/FVC%						
PEF						
FEF25-75%						
FEF200-1200	XXX.X	XXX.X	XX.X	XXX.X	XXX.X	XX.X

FIGURE 14. A TYPICAL TEST REPORT

FUNCTION/ALPHANUMERIC OPERATOR INPUT DEVICE

The operator should be able to enter the following information through an operator input device:

(a) Patient's name (last, first, initial)

(b) Patient's age

(c) Date/time of tests

(d) Patient's height (inches) and weight (pounds)

(e) Patient's sex

(f) Name of requesting physician

(g) Current diagnosis

(h) Whether patient is being tested pre or post broncho dialator.

(i) Lab pressure and temperature, and fractional conc. of O_2 and N_2 in room air.

The additional reuqirements that have to be met are:

(a) The operator must have some means for selecting whether or not he wants to save and make permanent copy of the data being currently displayed on the screen.

(b) The operator should be able to review the total list of parameters that could be measured and calculated by the various test procedures and delete any parameter which he considers unnecessary.

(c) The operator should be able to alter the threshold flow rate beyond which the volumes are measured during the forced vital capacity maneuver.

The operator input device can be a series of thumbwheel switches and some pushbutton switches. But considering the number of parameters to be entered and manipulated, it is proposed that a function keyboard be used.

CHAPTER V

DATA COMPUTATION AND ANALYSIS REQUIREMENTS

This section details the data computation and analyses requirements for the system, analyzes the alternative means for satisfying them and outlines one way for implementation.

Although varying in quantity and/or complexity, every test procedure has some data analysis requirement. They are as follows:

(a) Spirometry (Vital Capacity):

The flow rates for 1 minute of tidal breathing is digitized and integrated to get volume. The volume peaks are detected to keep count of the respiration rate. The volume excursion during each cycle is the tidal volume. The tidal volume reported is the average value over the one minute period. The average minimum volume determines the "resting expiratory level" and is designated the volume of 0.0 litres for future reference. Now when the patient inspires maximally to reach the maximum inspiratory level, the integrated flow rates give volume and the difference between the maximum volume and the resting expiratory level is the inspiratory capacity. Similarly the expiratory reserve volume is the difference between the resting level and the maximum volume the subject is able to expire. The IC and ERV are repeated and the reported value is the average of the two trials. IRV and VC can be now calculated by simple data manipulation.

All the parameters measured here are in ATPS and must be corrected to BTPS.

(b) Spirometry (Forced Expiratory Vital Capacity):

The flow rates for a forced expiration maneuver is obtained and has to be integrated to get volume. The flow rates are monitored and the point where it crosses a threshold value (+200mL/second) is designated a value of t = 0 and V = 0L. The samples are accepted till the volume reaches a maximum steady level (difference between two consecutive volume data points less than 20 mL). This maximum volume figure is FVC. The volume expired upto 1 sec. after t = 0, is the FEV 1.0. The peak expiratory flow is the maximum flow rate measured during the maneuver. The FEF 25-75% is the average rate of flow during the middle half of the forced expiratory flow. To obtain it, calculate 25% and 75% points by multiplying FVC by .25 and .75 respectively. Determine time required to reach these points, t_1 and t_2. $\text{FEF25-75\%} = \frac{0.5\ \text{FVC}}{(t_2 - t_1)}$

The FEF200-1200 is the average flow rate for the liter of gas expired after the first 200 mL during forced expiration. The time interval from the 200 mL point to the 1200 mL point is determined to be $(t_2 - t_1)$. $\text{FEF200-1200} = \frac{1.0\ \text{L}}{(t_2 - t_1)}$.

All the parameters measured here are in ATPS and must be corrected to BTPS.

(c) Spirometry (Forced Inspiratory Vital Capacity):

The FIVC is calculated exactly the same way as FEVC with time t = 0 set at the point where flow exceeds -200 mL/sec. The peak inspiratory flow rate is the maximum flow rate sampled.

During the maximum voluntary ventilation maneuver, the respiration rate is calculated, and displayed on the screen. When the operator sends a command signal that the subject is maintaining a steady rate, flow rates are integrated for the next 10 seconds to give volume.

MVV = (measured volume for 10 seconds x 6) L/min.

The FIVC, PIF and MVV values are in ATPS and have to be converted to BTPS.

(d) Flow-Volume Loop:

The flow rates for a cycle of forced inspiratory and forced expiratory maneuver are obtained and integrated to give volume. All the flow and volume values are stored till the flow rate reaches zero, and are used to generate the loop which has volume as x-axis and flow as the y-axis. Searches are initiated to locate the maximum volume (should occur at the end of inspiration, flow = 0), maximum negative (PIF) and positive (PEF) flow rates, and flow rates at 50% of maximum volume during both inspiration (FIF50%) and expiration (FEF50%).

(e) Nitrogen Washout:

Single Breath: The flow rates and percentage nitrogen concentration values are obtained from the pneumotachometer and the mass spectrometer. The flow rates are integrated to give volume, and a graphic plot is generated between % N_2 and volume. The plot stops when the volume reaches a steady state (change in volume between two successive samples is less than 10 mL). A square front CB (Figure 8) is constructed by numeric techniques so that areas ABP and CDP are equal. VDAN is the volume expired upto the square front, CB.DELTAN2 is obtained by identifying the difference in % N_2 concentration between the points when 750 mL and 1250 mL of gas has been expired. Next a search is initiated after a volume of 1250 mL has been expired for the point starting which the % N_2 concentration changes by 0.4% within 5 samples. It is assumed that the flow rates and the nitrogen concentration are each sampled at the rate of 20 samples/second. The volume of gas expired between this point and the end point is the closing volume. The alveolar ventilation can now be calculated by fetching the respiration rate and tidal volume values and using the formula

$$'V_A = f(V_T - VDAN)$$

Multiple Breath: Sampling of flow rates start when the operator indicates that the subject has started inhaling from a 100% oxygen source and continues for the next 7 minutes. The flow rates for this period are integrated to give the total expired volume V(total). At the end of the period, the N_2 concentration value is obtained from the mass spectrometer.

FRC is now calculated as

$$FRC = \frac{\%\ N_2\ (Final) \times Expired\ Volume}{\%\ N_2\ (Atmospheric)}$$

RV, TLC and RV/TLC % values can be easily calculated.

The inspired gas distribution index is calculated from:

$$IDI = \frac{V(total) - f(VDAN)}{FRC \times \log 72}$$

(f) Helium Dilution:

The helium concentration values are obtained from the mass spectrometer. The volume of He added to the tank is obtained through the operator input device and using the initial He concentration value, the initial volume of gas in the tank is calculated. The first two minutes of data is rejected and then each successive value of He concentration is compared to the one preceeding it. When the difference between two successive samples is less than 0.05%, the sampling is stopped. The final He concentration value is now known and the FRC and subsequently the RV and TLC values are calculated.

(g) Diffusing Capacity:

During the single breath diffusion test, the concentrations of CO and He are obtained for 10 seconds. The initial concentration values should be 0.3 and 10% respectively. F_{ACOt_1} is calculated as (0.3 x 10)/He concentration at the end of 10 seconds. The alveolar ventilation value is fetched from the Single Breath N2 washout test data. The barometric pressure is obtained through the operator input device. Now DLCO can be calculated by equation in Chapter III.

During the steady state diffusion test, the concentrations of CO are obtained for 30 seconds. The concentration values of CO at t = 0, 10, 30 seconds are accepted, and the rest of the data rejected. The tank volume is obtained through operator entry device and the DLCO is calculated.

(h) Body Plethysmography:

The flow rates for normal breathing are obtained and integrated to give volume. They are monitored to identify the point where flow rate is zero and the volume is a positive maximum (end expiration point). At this point a control signal is sent to the bodybox to close the mouthpiece shutter, while the subject continues to make his respiratory effort of inspiration.

Using Boyle's Law:

$$\text{Box volume} + \Delta V = \frac{\text{Box pressure before shutter closure}}{\text{Box pressure after shutter closure}} \times \text{Box volume}$$

and if thoracic gas volume is V,

Inital mouth pressure x V = final mouth pressure x (V + ΔV)

Thus TGV can be calculated.

The airway resistance is calculated from the difference in atmospheric and alveolar pressure after the mouthpiece shutter closes momentarily after end-expiration divided by the average flow when the shutter opens. Conductance is calculated as the reciprocal of the airway resistance.

(i) Blood Gas Analysis:

The digitized partial pressure values for blood O_2 and CO_2 are collected for 10 seconds and the average of these 50 values for each (assuming sampling rate $\simeq$ 10/sec) are calculated to give P_{aO2} and P_{aCO2}.

The values of fractional concentration of inspired oxygen (same as concentration of oxygen in room air) and barometric pressure are obtained thru the operator input device and the P_{AO2} is calculated, assuming RQ = 0.8. Next the calculated parameters P_{AO2}, P_{aO2} are used to calculate percentage physiological shunt.

In addition to the data manipulation required for the test procedures, there must be some means for doing the following:

(a) store patient specific data like name, I.D.number, age, sex, height, weight, attending physician and test condition data which are obtained from the operator through the operator input device. This information is required for calculating certain test parameters and predicted normal values.

(b) calculate predicted normal values of test parameters on the basis of equations in Appendix A and data obtained during patient entry through the operator input device.

(c) generate correction factors for the calibration flow rates on the basis of O_2, CO_2, N_2 and H_2O concentrations in the test gas at the onset and every two seconds thereafter on the basis of four simultaneous equations (3).

(d) generate formated final test report for each test procedure which includes certain selected patient information, test results with predicted normal values and graphical display, if necessary. This data must be formated to enable easy transfer of data to the storage device.

(e) retrieve data from the mass storage device and utilize it to generate patient or parameter specific trend plots.

(f) handle mathematical functions like multiply/divide, logarithms and variable arguements to constant power calculations.

The three approaches which could be taken to satisfy the data computation and analyses requirements are:

(a) hardwired logic approach in the form of smart signal conditioning modules,

(b) microprogrammed approach using resident PROM as the controller,

and, (c) microprocessor based system approach.

As discussed earlier, the pulmonary function test regimes are yet to be finalized or universally accepted. Both, the test parameters and the predicted normal value equations, are continually being changed and updated. Considering this it will be ill advised to take the inflexible hardwired logic approach.

The resident PROM approach has two basic advantages, it is capable of reaching high speeds and makes more efficient use of memory elements. However, this application area does not require any high speed capability and considering the way the price of memory is going down, both the advantages of this approach do not appear to be very important. The resident PROM approach requires logic circuitry around it to make it

functional. The PROM controller has to be modified along with peripherical logic to make any required changes rendering it very inflexible. These systems are also hard to debug. All this could add up to an approach which will have limited flexibility and would require higher development cost.

Considering the complexity of the system, the number of calculations required and inherent requirement for flexibility, it seems that the microprocessor-based approach is most suitable for this application. Adding to it the existing experience of the medical engineering designers with micro-computers, the ease of generating software with a wide choice of languages and the declining cost of microprocessors leads one to select the microprocessor system approach over the other two.

It is now necessary to determine the software requirements for this system. One the basis of the data computation and analyses requirements identified earlier, the system software can be classified into three categories:

(1) System Routines,

(2) Utility/Math Routines,

and, (3) Application Programs.

(1) The following are considered to be necessary in the system routines:

(a) Main control program,

(b) Interrupt handler routine,

(c) Clock handler routine,

(d) Sampling routine,

(e) Keyboard entry routine,

(f) Data format routine,

(g) Display routine,

(h) Hardcopy driver routine,

and, (i) Disc I/O routine (optional).

(2) Utility/Math Library should contain the following:

(a) Multiply/Divide,

(b) Natural logarithm calculation,

(c) Base 10 logarithm calculation,

(d) Decimal/Binary conversion,

(e) Binary/Decimal conversion,

(f) Variable arguement to constant power calculation, required during predicted normal values calculations,

(g) ATPS/BTPS conversion to convert data from ATPS to BTPS units when called upon to do so by the application programs,

(h) Inches/Centimeters conversion to convert patient height to centimeters,

(i) Pounds/Kilograms conversion to convert patient weight to kilograms,

and, (j) Body Surface Area calculation from patient height and weight when required for predicted normal value calculations.

(3) There has to be one application program for each of the test procedures. The details of these nine programs appear earlier in this section and could be called:

(a) Spirometry - Vital Capacity test routine,

(b) Spirometry - FEVC test routine,

(c) Spirometry - FIVC test routine,

(d) Spirometry - Flow/Volume Loop test routine,

(e) Nitrogen Washout test routine,

(f) Helium Dilution test routine,

(g) Diffusing Capacity test routine,

(h) Body Plethysmography test routine,

(i) Blood Gas test routine.

Additionally it requries:

(j) Patient Entry routine which creates patient specific data files and accepts data from operator I/O device,

(k) Calibration routine for each of the transduced parameters,

(l) Calibration correction factor routine which calculates correction factors for the flow rates on the basis of gas concentration values,

(m) Predicted normal value calculation routine which calculates the values according to the according to the equations in Appendix A,

(n) Formatted Test Report routine which generates the final test report in the desired format,

(o) Patient Trend Report routine which creates trend plots for desired parameters for patients who areanalyzed by the system more than once,

and, (p) Parameter Trend Report routine which generates trend plots for desired parameters across the patient population.

MICROCOMPUTER SYSTEM :

The microcomputer system should have the following components:

(a) Central Processor Unit

(b) Read Only Memory for programs

(c) Random Access Memory for data storage

(d) Priority Interrupt

(e) Interval timer (1 sec - 256 secs)

(f) A/D Converter

(g) Analog multiplexer - eight channels

(h) Digital I/O cards - four cards

Optional components: (for floppy disk option)

(a) DMA

(b) Disk Controller

ANALOG-TO-DIGITAL CONVERTER AND MULTIPLEXER:

The system will require a multiplexer with upto 8 channels and an analog-to-digital converter for digitizing any one or all of the system's input waveforms or signals. The eight input signals to the multiplexer are:

(a) Flow rates from the pneumotachometer and temperature profile data from its temperature sensor.

(b) Four channels of partial pressure waveforms from the mass spectrometer.

(c) Body box pressure and mouth pressure data during body plethysmography test.

The Analog Multiplexer should have the following:

(i) Eight channels

(ii) Single ended high level signals (±10 volts)

(iii) Binary addressing capability

(iv) Settling time < 10 μ seconds

Functional Specifications for A/D Converter:

Resolution: at least 8 bits

Sampling rate: 50 samples per seconds

Accuracy: ±½ l.s.b.

Conversion times: ≤ 1 millisecond

Temperature Coeff:

Gain ±20 ppm/^{o}C

Zero ± 50 μV/^{o}C

Input Voltage Levels: ±10 volts

Output signals: Parallel TTL compatible

Output Code: 2's complement positive true

Output levels: "0" < 0.4 volts

"1" > +2.4 volts

Operating temperature: -5^{o} to +50^{o}C

Storage temperature: -30^{o} to +65^{o}C

Humidity: 5% to 95% (non-condensing)

The sampling rate figure was arrived at on the basis of the requirements that each of the flow rates and gas concentration values have to be sampled at the rate of 20 samples per second.

MICROPROCESSOR REQUIREMENTS:

The system requirements call for a microprocessor with at least 8 bits and two's complement arithmetic. The application does not require a high speed processor. Any processor with cycle time of under 250 microseconds is adequate. It should have an interrupt line with priority resolution and should have compatibility for DMA channels for high speed device transfers.

The memory requirements for the total system cannot be accurately determined now, although it should require both random access memory and read only memory.

The system requires four digital input/output cards with 8 bit information in or out in order to achieve the following:

(i) Functional keyboard interface

(ii) Body plethysmograph interface

(iii) Control signal to two shutters in the pneumotachometer system.

CHAPTER IV
PRODUCT CONCEPT

This section describes a possible product concept for the Pulmonary Function Lab System. The system will have the following:

(1) A pneumotachometer for respiratory flow measurements. Detailed specifications for this unit have been outlined in Appendix B. The Fleisch pneumotachograph will have to be modified or redesigned so that it can meet the specifications for the proposed pneumotachograph. The newly released variable orifice Spiroceptor by Siemens meets most of the desired specifications. The pressure sensor could be developed in conjunction with SSEC.

(2) A mass spectrometer device for both respiratory and blood gas analyses. Detailed specifications for this unit have been outlined in Chapter IV. The Honeywell Pulsed Gas Analyzer developed by CRC could be used for this application. It has several useful features including compact size, low sample volume requirements (critical during blood gas analysis) and a possible price which is lower than that of comparable units available in the market. However, some modifications will be required especially in the signal conditioning circuit design, and special attention must be given to minimize its operational complexity.

(3) A body plethysmography unit. Specifications for this unit are outlined in Chapter IV. It is recommended that this unit be purchased from an outside vendor and incorporated into the main system.

(4) Three signal conditioning modules. The signal conditioning required for all the four basic spirometry test groups and the helium dilution, nitrogen washout and diffusion capacity tests are very similar and can be incorporated into one module. However since the last three are not basic test procedures and may not be desired by every customer, it is advisable to have their signal conditioning circuitry on separate piggy back cards mounted on to the basic spirometry test card. The body plethysmography and blood gas analysis signal conditioning will be done in separate modules.

(5) A multiplexer and A/D converter. Their requirements have been outlined in Chapter V.

(6) A microprocessor system for system control and data analyses. The system will also be responsible for automated calibration of the instruments, correction of flow rate data by gas concentration values from the mass spectrometer , calculation of predicted normal values and generation of patient test reports and trend plots. The system will also send control signals to operate shutters and valves where necessary. Details of its specifications are outlined in Chapter V.

(7) A graphic/alphanumeric display unit capable of meeting specifications outlined in Chapter IV.

(8) A hardcopy unit capable of printing frozen graphic/alphanumeric data on the display unit. Specifications appear in Chapter IV.

(9) A function/alphanumeric keyboard unit to enable operator entry of patient specific data, test conditions and control data as outlined in Chapter IV.

(10) An optional mass storage device like disks or cassettes for storage of patient specific data. Detailed specifications for this unit appears in Chapter V.

A possible packaging concept has been shown in Figure 15 and 16. The main frame will include the signal conditioning units, mass spectrometer, display, hardcopy, function keyboard, microprocessor system and the optional mass storage device. The pneumotachometer will be attached to this unit. The body box will be a separate unit. Since the system is not expected to be moved around, they are not mobile units.

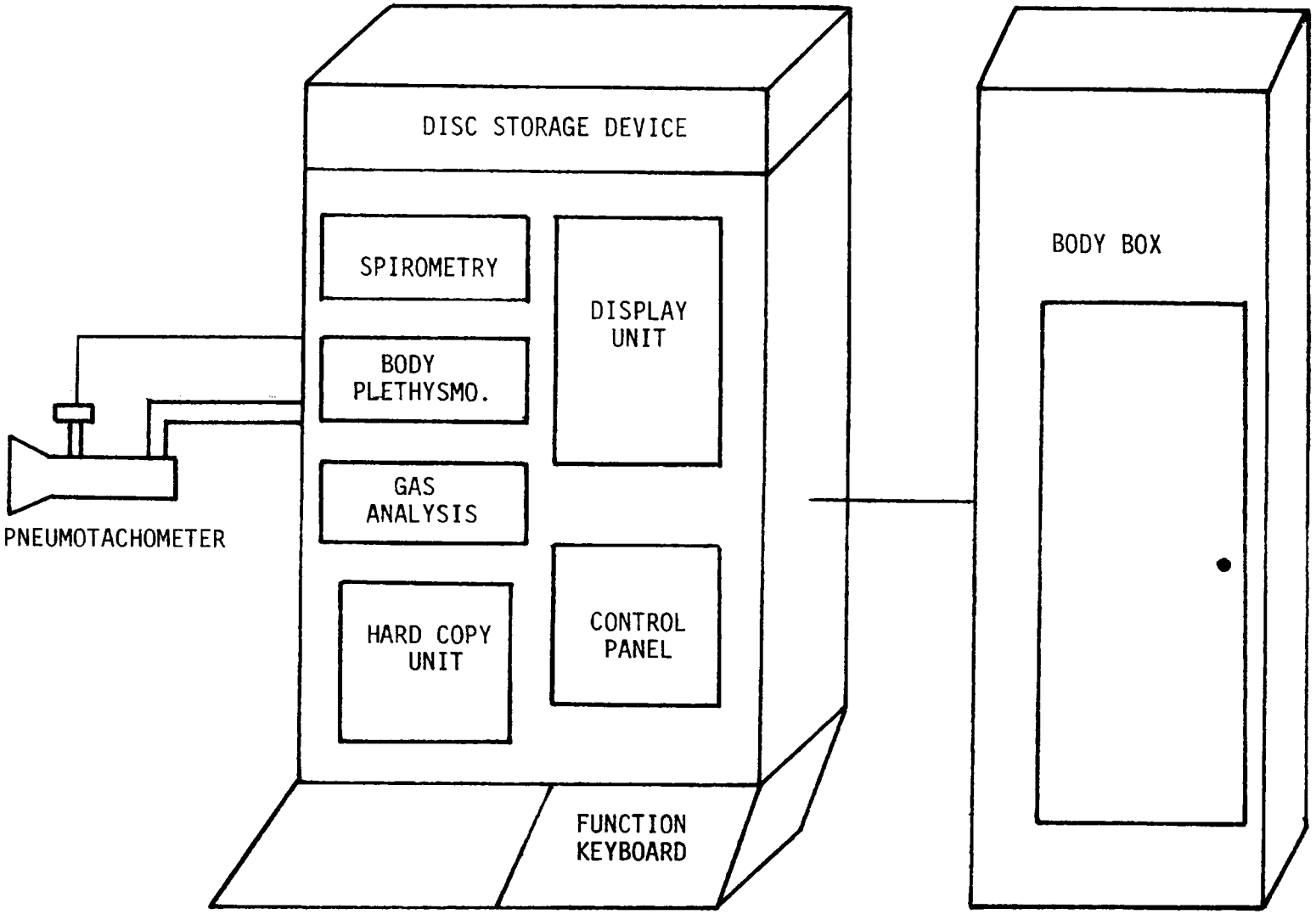


FIGURE 15. PRODUCT PACKING CONCEPT

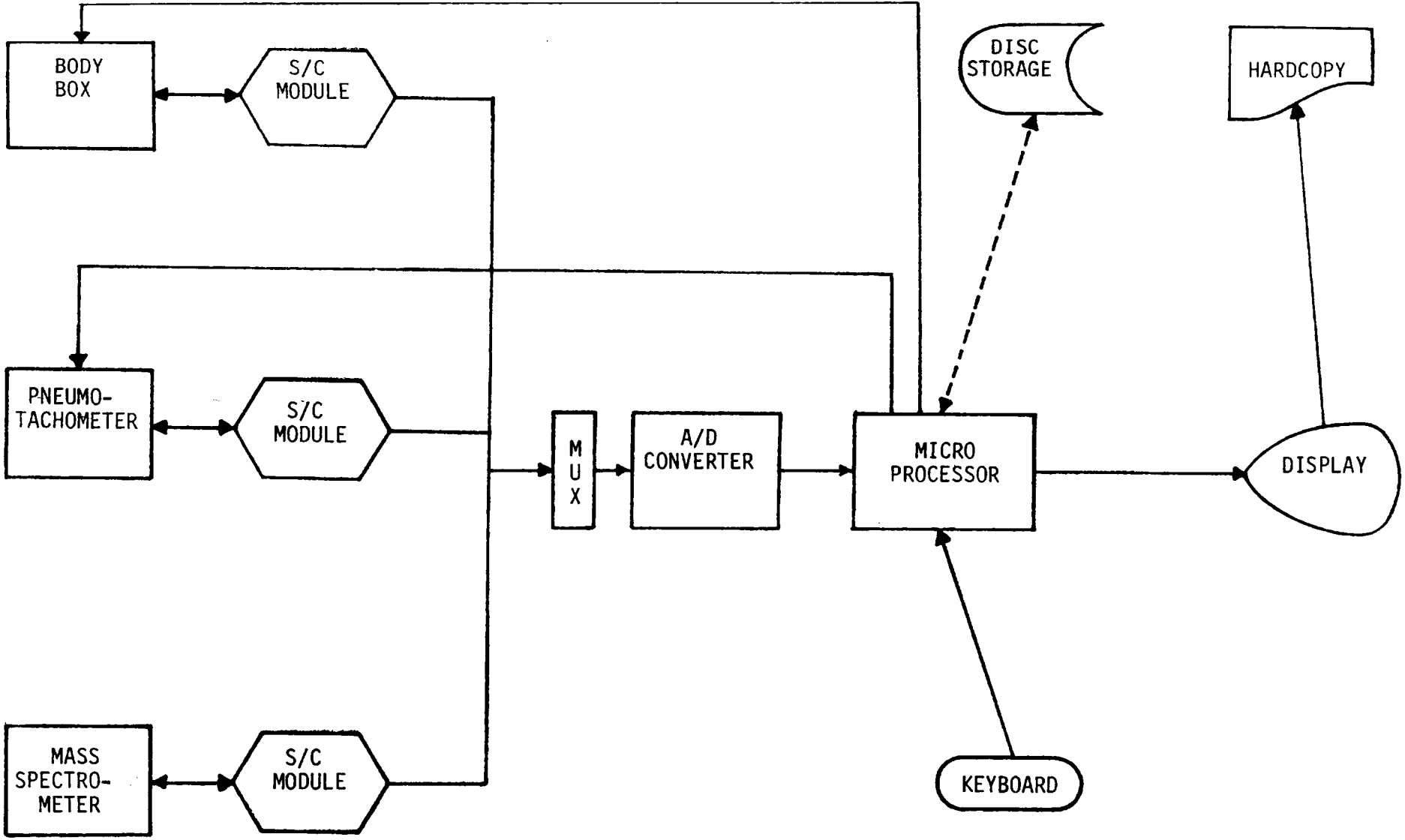


FIGURE 16. FUNCTIONAL BLOCK DIAGRAM

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APPENDIX A

REQUIRED CALCULATIONS

Required equations for data computation;

Height in cms. = Ht. in inches x 2.54

Weight in kgs. = Wt. in pounds x 0.4536

Body Surface Area: (in square meters)

$$S = 71.84\ L^{0.725}\ W^{0.425} \quad \text{(Debois' eqn.)}$$

$$= \frac{H^{0.3}}{10^4}\ (3.2\ W^{0.7825} - 0.0188 \log W) \quad \text{(Boyd's eqn.)}$$

For a component in a gas mixture:

Partial pressure at body temperature, saturated with water vapor = $\frac{\%\ \text{in gas sample}}{100}$ (Atmospheric pressure - 47) in mm Hg.

$$\text{Volume in BTPS} = \text{Volume in ATPS} \times \frac{P_{atmos} - P_{H2O}}{P_{atmos} - 47} \times \frac{310}{(273 + T)}$$

where P_{atmos} = atmospheric pressure in mmHg

P_{H2O} = vapor pressure at pneumotachometer temperature,

and T = pneumotachometer temperature in ^{o}C.

Item No.	Parameter (units)	Male	S.D	Ref	Female	S.D	Ref
7	Vital Capacity (L.)	0.052H-0.022A-3.6	.58	10	0.0545H-0.0105A-5.12	.498	1
8	Forced Vital Capacity (L.)	0.052H-0.022A-3.6	.58	10	0.0508H-0.032A-3.02	.52	5
9	Forced Exp. Vol. (L.) 0.5s	0.02H-0.024A+0.24	.51	10	0.678xFVC		13
	1.0s	0.037H-0.028A-1.59	.52	10	0.025H-0.022A-0.62	.40	7
	3.0s	0.93FVC		12	0.93xFVC		12
10	FEV0.5/FVC %	(Pred (FEV.5/FVC))x 100		-	same as male		-
	FEV1.0/FVC %	91.8-0.373A		4	92.1-0.261A		4
	FEV3.0/FVC %	(Pred(FEV3.0/FVC))x 100		-	(Pred(FEV3.0/FVC))x 100		-
11	Peak Exp. Flow (L./min)	(3.95-0.0151A)H		11	(2.93-0.0072A)H		11
12	FEF25-75% (L./min)	1.11H-2.7A+150.78	67.2	14	1.417H-1.8A+33.06	48	14
13	FEF200-1200 (L./min)	2.57H-282A+120.6	99.6	14	3.425H-2.16A-151.92	71.4	14
14	Forced I. Vital Capacity (L)	0.052H-0.022A-3.6	.58	10	0.0508H-0.032A-3.02	.52	5
15	Max. Insp. Flow Rate (L./min)	6.18H-3.3A-545		16	0.7(6.18H-3.3A-545)		16
16	Max. Voluntary Ventilation (L./min)	(86.5-0.522A)S		3	(71.3-0.474A)S		3
33	Airway Resistance (Raw)						
	(cm H_2O/L./sec)	1/(0.3xTGV)low		6	same as male		6
		1/(0.13xTGV)hi			same as male		
34	Airway conductance (L./sec/cm H_2O)	1/(Pred. Raw)		16	1/(Pred. RAW)		16
20	Closing Volume (mL.)	5.62+3.57A)xV.C (in liters)		2	(28.12+2.93A)xV.C. (in liters)		2

/27	Functional Residual Cap (mL)	57.8H+16A-40W-4240	610	9	55.9H-30W-4910	450	9
/28	Residual Volume (mL)	21.6H+23.9A-16.3W -1680	415	9	29.3H+7.6A-3730	348	9
/29	Total Lung Capacity (mL)	75.6H-18.5W -4690	730	9	73.1H-16.3A-6280	522	9
/30	RV/TLC %	(Pred(RV/TLC)) x100		16	(Pred(RV/TLC)) x100		16
31	DLCO(Single Breath) mL/ min/mmHg	$3.75V_A$(STPD)-.153A +19.93		8	$5.38V_A$-0.083A+7.72		8

H is height in cms; A is age in years; S is surface area in M^2; W is weight in Kgs.

Item No.	Parameter (unit)	Male children (5-16 years)		Female children (5-16 years)	
7	Vital Capacity (L.)	$4.4\times10^{-6}\times H^{2.67}$	15	$3.3\times10^{-6}\times H^{2.72}$	15
8	Forced Vital Capacity (L.)	$4.4\times10^{-6}\times H^{2.67}$	15	$3.3\times10^{-6}\times H^{2.72}$	15
9	Forced Expir. Volume (L.) 1.0s 3.0s	 $2.1\times10^{-6}\times H^{2.8}$ 0.93xFVC	 15 16	 $2.1\times10^{-6}\times H^{2.8}$ 0.93xFVC	 15 16
10	FEV1.0/FVC%	86	15	86	15
11	Peak expiratory flow (L./min)	5.243xH-425.6	15	5.243xH-425.6	15
12	FEF25-75% (L./min)	0.0514H-4.38	17	0.0514H-4.38	17
14	Forced Insp. V.C. (L.)	$4.4\times10^{-6}\times H^{2.67}$	15	$3.3\times10^{-6}\times H^{2.72}$	15
15	Max. Insp. Flow Rate (L./min)	3.64xH-315.6	17	3.64xH-315.6	17
16	Max. Voluntary Vent (L./min)	1.276H-99.51	15	1.276H-99.51	15
33	Airway Resistance (Raw) (cm H_2O/L./sec.)	1/(0.3TGV)low normal 1/(0.13TGV) high normal	 6	1/(0.3TGV) low normal 1/(0.13TGV) high normal	 6
34	Airway conductance (Raw)	1/(Pred. Raw)		1/(Pred. Raw)	
22/27	Functional Res. Cap. (mL)	$0.75\times10^{-6}\times H^{2.92}$	15	$1.78\times10^{-6}\times H^{2.74}$	15
23/28	Residual Volume (mL)	$4.41\times10^{-6}\times H^{2.41}$	15	$4.41\times10^{-6}\times H^{2.41}$	15
24/29	Total Lung Capacity (mL)	$5.6\times10^{-6}\times H^{2.67}$	15	$4.0\times10^{-6}\times H^{2.73}$	15
25/30	RV/TLC %	(Pred. RV/Pred. TLC)x100	15	(Pred. RV/Pred. TLC)x100	15

Note: There are no acceptable predicted value equations for children below 5 years.

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APPENDIX B

PNEUMOTACHOMETER SPECIFICATIONS

This appendix details the functional requirements for a spirometry device.

The Pulmonary Function Lab. Systems, Respiratory ICUs and the Cardiac Stress Testing Lab. Systems require some means of measuring the inspiratory and expiratory flows and volumes of gases from the lungs to determine the proper functioning of the lungs, its ability to exchange gases and the oxygen consumed by the person under different stress levels, and to monitor the proper functioning of a respirator.

The flow which has to be measured can vary over the range of 0-600 litres/minute. The inspired air is essentially room air with 78% N_2 and 21% O_2 at ambient temperature and the expired gas contains 74% N_2, 15% O_2, 4.2% CO_2 and saturated with water vapor at body temperature of about $37^{o}C$.

One means of measuring the respiratory gas flows is by using a pneumotachometer. It consists of a pneumotachograph which is essentially a flow meter consisting of a large number of straight tubes with 0.8 mm diameter and honeycomb-like cross-section. It works on Poiseuilles' Law that states that under laminar flow conditions, in a straight rigid tube, delivery is proportional to pressure loss per unit of length. The continuous measurement of the pressure difference between two points on the tube gives a differential pressure curve whose ordinates represent the velocity of the air current. This differential pressure can be measured by a pressure sensor to obtain an electrical output proportional to the flow. Volume can then be obtained by simple integration of the flow.

The differential pressure measured at two points along the tubes of the pneumotachometer is given by

$$P_1 - P_2 = \frac{V}{t} \cdot n \cdot \frac{8\,l}{\pi . r^4} \qquad \text{eqn (1)}$$

where V = volume l = length of tube

t = time r = tube radius

n = vicosity

Therefore changes in temperature, pressure, humidity, and the composition of the respiratory gas affect the various factors of Poiseuilles' Law, thus introducing errors to this method if they are not considered. If the instrument is calibrated with room air, error is introduced when measuring expired flows as there is change in gas composition and therefore in viscosity. However correction factors can be used to take care of these errors if the composition of the gases and their temperature and pressure are known. (2,5)

The respiratory flow can be measured alternatively using water bell spirometers which have poor frequency responses and are cumbersome to use, dry rolling seal or wedge type with the problem of poor dynamic responses, thermistors (with linearizing circuit) or thermocouples which have long response times and the hot wire anemometer which is non linear and rather unstable (See Table BI). Beckman has recently introduced an ultrasonic flow probe, but no reports are available at this point regarding its functional capability. In its minimum configuration it costs $3,300. The pneumotachometer with its excellent linearity within its range and fast response time seems to be an excellent candidate for making respiratory flow measurements. (1)

However commercially available pneumotachographs (See Table BI) have one major drawback. In order to accurately measure flows over the whole range of interest (0.1 - 600 L./min.), four separate flowheads have to be used. The reasons for this is as follows:

The gases flow through the pneumotachograph under capillary conditions following a laminar flow pattern as long as the flow rate does not exceed certain limits beyond which the flow pattern becomes turbulent and the pressure differential response to flow becomes non-linear. Therefore with a small size, the linearity of response is limited to slow flows. With a large size, on the other hand, a large dead space is added to the patient's airways and thereby the flow profile is altered.

Conceivably, the four flowheads can be replaced by one which has a variable cross section along its length complimenting the flow profile of gases passing through the head. Siemens has just released a single head pneumotachograph (SPIROCEPTOR) which claims a <2.5% error to actual value over a 0-16 L./Sec. range. Although the actual design of this product is not known, but its name (variable orifice) seems to suggest some modification to existing Fleisch pneumotachograph.

Therefore the primary requirement is to design a single flowhead with the following characteristics:

(1) Measure flows between 0 - 720 L/min with 100% overrange.

(2) Accuracy: $\pm$1% full scale for flows over 0.1 L./Sec [3].

(3) Dead Space: Less than 50 ml.

(4) Resistance to Flow: 0.35 cm H_2O/L/Sec. or less.

(5) Frequency Response: DC to 25 Hz.

(6) Response Time: Less than 25 msec.

(7) Mouthpiece Diameter: Greater than 2.5 cm [3].

(8) Sensitivity: 1 mmH_2O/1.0 L./min.

(9) Flowhead should be heated to avoid condensation of moisture inside it.

(10) Available Excitation: 2.5, 5.0 and 10V.

(11) Comparative Sell Price: $950 - $1100 (for 4 flowheads).

The differential pressure transducers being used today are either the variable reluctance type or the bonded strain gauge type (See Table BII). Both of these need large displacements to operate and provide adequate outputs only with large diaphragms and considerable volume displacements. Currently available pressure transducers are connected to the output ports of the pneumotachographs by long lengths of tubing (10" - 15" long). Published literature [6] shows that these long coupling lines together with large and uneven compartment volumes produce considerable errors due to hydraulic effect of the line. The silicon strain gauge with its large gauge factor should need a small diaphragm and it should be possible to reduce considerably the length of the coupling lines to gain in overall accuracy, and reduce dead space.

The differential pressure sensor should meet the following specifications:

1. Pressure Range:

Operating Full Scale Range:	±600 mm H_2O.
Gauge or Absolute:	Gauge
Over Pressure Range:	1000 mm H_2O

2. Accuracy: ±1% Full Scale.

3. Sensitivity: 1 mV/10mm H_2O at rated excitation.
4. Temperature Sensitivity: 0.1 f.s./^oC over operating temp. range.
5. Operating Temperature Range: 30^o - 40^oC.
6. Non-Operating Temperature Range: -10^oC to $+65^oC$.
7. Available Excitation: 2.5V, 5.0V, 10V.
8. Frequency Response: DC to 25 Hz.
9. Physical Consideration: Minimum dead space from pneumotachograph to sensor.
10. Comparactive Sell Price: $350.00 - $450.00.

According to Poiseuille's equation, (eqn. 1) the pressure drop along the pneumotachograph is dependent on the viscosity of the gas mixture. Therefore in order to maintain accuracy in its reading, the instrument has to be calibrated with gases whose compositions are as close as possible to the test gas under consideration. This leads to tedious calibration procedures and commercially available systems today, which require use of exotic calibrations gases, are still not able to adequately account for changes in the test gas composition.

All this can be avoided if the pneumotachograph is integrated with a gas analyzer. This allows the calibration to be carried out by simple room air and if composition and temperature of the test gases are know, correction factors can be calculated [2,5] which eliminate the errors due to calibration with only room air. The total system will then consist of a pneumotachometer with a multigas analyzer (like the mass spectrometer) and a differential pressure transducer, all under a central processor control which corrects the measured values (figure 19).

A total pulmonary function lab system with a gas analysis instrument directly interfaced with the pneumotachometer also allows several additional tests to be performed which are useful and are regularly performed for diagnosis of respiratory diseases. In absence of one versatile analyzer like a mass spectrometer, important and commonly used pulmonary function tests (like the Helium dilution, Nitrogen washout, Oxygen consumption and diffusion capacity) would require four separate analyzers (He analyzer, N_2 anzlyer, CO analyzer and O_2 analyzer). These four separate analyzers cost in excess of $12K, and none of them are considered satisfactory.

In addition, it is very common to perform blood-gas analysis in a pulmonary function lab. The on-line mass-spectrometer will be able to do this analysis.

At present, the Pacific Medical Center in San Francisco has one such integrated pneumotachometer and mass spectrometer system for Respiratory Monitoring of Intensive Care patients [7]. The University of Colorado Medical Center has a similar system with a flow transducer (in this case a hot wire anemometer) and a mass spectrometer integrated together. It seems BENDIX is the only manufacturer (PFA-5) at present who provide a flow meter with their miniaturized mass spectrometer (2-99 amu range/ 5 channels).

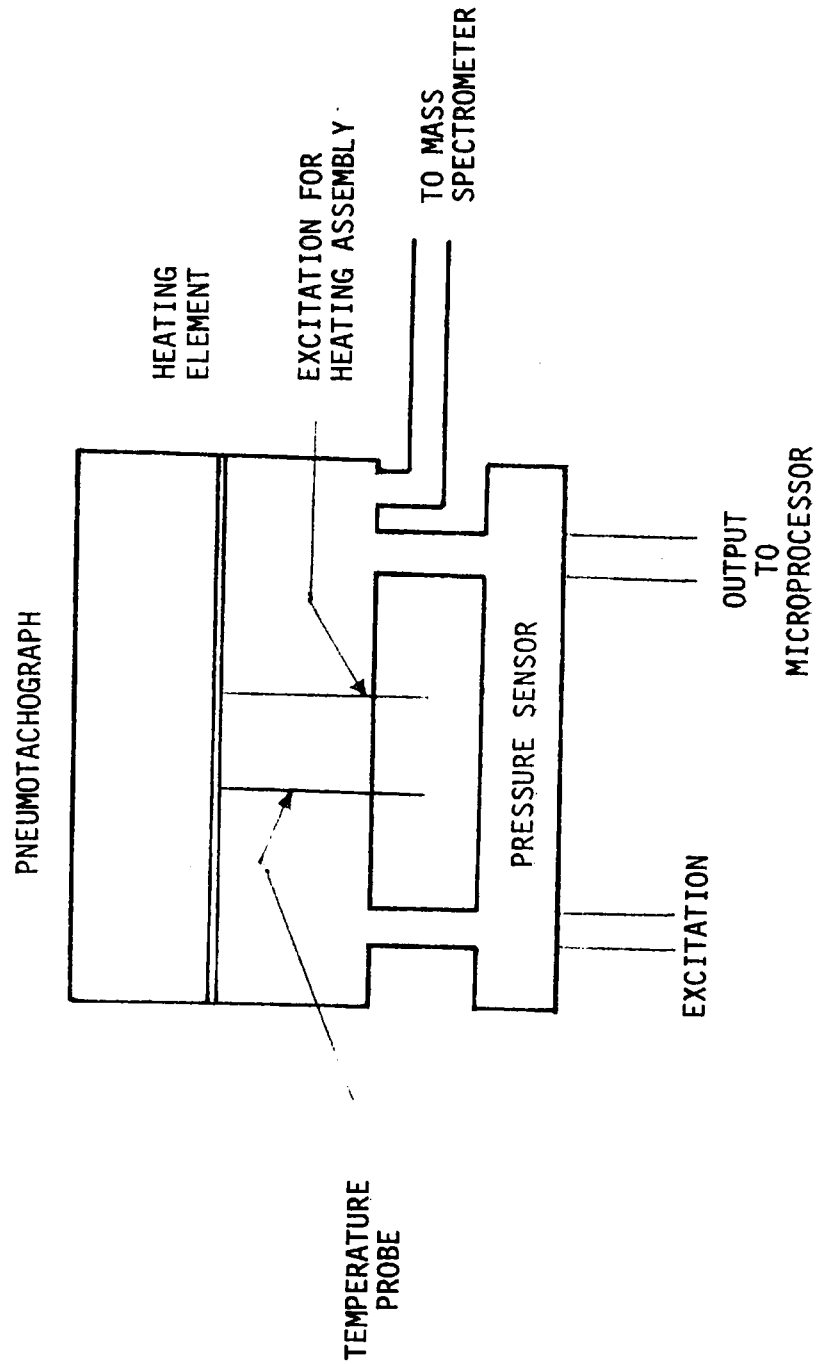

FIGURE 19. PNEUMOTACHOMETER CONCEPT

TABLE BI. ALTERNATE METHODS FOR MEASURING RESPIRATORY FLOW RATES

ITEM	TRADE NAME	MANUFACTURER	FLOW DETECTION
I	Pulmo-Line 220	Cardio-Pulmonary Instruments Corp. P.O. Box 36424 Houston, Texas	Dry Rolling Seal ≈$2000
2	Ohio 842	Ohio Medical Prod. 3030 Airco Drive Madison, Wics.	Dry Rolling Seal
3	Dry Spirometer No. 06500	Warren E. Collins 200 Wood Rd. Braintree, MA 02184	Dry Rolling Seal $886
4		Med Sciences Electronics Quaker Hwt Jcn. Rte 146 Uxbridge, Mass. 01569	Wedge
5	Vitalograph	Vitalograph Buckingham, England	Wedge Bellows
6	Pulminor	Jones Medical Sciences 200 Windsor Drive Oak Brook, Illinois 60521	Bellows
7	Model 403	Monaghan 4100 Dry Creek Road Littleton, CO 80122	Thermistor
8		Datametrics 340 Fordham Road Willmingh, Mass.	Hot Wire
9	Donti	Canitron 580 Sylvan Ave Englewood Cliffs, New Jersey	Hot Wire
10	Vanguard DS 601 MF	Life Support Equipment Corp. 6 Gill Street Woburn, Mass.	Semi-pneumotach $1500
11	Digiflow 200	Este Instruments 1344 South 49th St Richmond, California	Semi-pneumotach
12	Digital Pneumotach Model 47303A	Hewlett Packard 175 Wyman Street Waltham, Mass.	Pneumotach

ITEM	TRADE NAME	MANUFACTURER	FLOW DETECTION
13	Spirostat	Marion Labs Kansas City, Missouri	Turbinometer
14	Expirometer	Warren E. Collins, Inc. 220 Wood Road Braintree, MA. 02184	Turbinometer
15	Tracor	See Vanguard	
16	F-V Pneumotach Model 100	Cardiopulmonary Instruments	F-V Pneumotach $2150
17	Lamellated Spiroceptor	Siemens	Pneumotach
18	Variable Orifice Spiroceptor	Siemens	Pneumotach
19	PR-30	Beckman Instruments 3900 River Road Schiller Park, Illinois 60176	Ultrasonic Spirometer $3,300.

TABLE B II

COMPARATIVE ANALYSIS OF COMMERCIALLY AVAILABLE

LOW RANGE DIFFERENTIAL PRESSURE TRANSDUCER

MANUFACTURER MODEL NO. TYPE	HEWLETT-PACKARD 270 LVDT	VALIDYNE MP-45 LVDT	STATHAM PM-14 BONDED STRAIN GAUGE
Range (mm H_2O) Overrange	±400 2000	+2.5, 10, 20, 50, 100 ±800	±25 ±180
Linearity	1% F. S.	±½% best st. line	
Output/Sensitivity	80 μV/V/mmH_2O	25 mV/V f. s. nom.	±5 mV/V f.s.
Stability	.04 mmH_2O/^oF	.02%/^oF	
Hysterisis		.1 f.s. excursion	
Volume (pr. cavity)	4.0 cc	0.16 cc	
Vol. Displacement	1.5 mm^3/mm H_2O	15 mm^3	
Thermal Zero Shift		.01% f.s./^oF	
Zero Balance		< 10% f.s.	
Differ. Balance	Output ≃.01% Appl. Pressure		
Excitation		5V rms, 3k-5 kHz	5V (AC/DC)
Price	$300	$300	$400

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APPENDIX C
USER SURVEY

It is important to point out at the onset that this section on survey of users is not complete. Due to lack of resources and interest, only 6 hospitals were actually surveyed. They were:

(1) Fitzsimmons Army Hospital, Denver, CO.

(2) National Asthma Center, Denver, CO.

(3) National Jewish Hospital, Denver, CO.

(4) General Rose Hospital, Denver, CO.

(5) Denver General Hospital, Denver, CO.

(6) Scott and White Hospital, Temple, Texas.

The following sources were also used to determine user needs:

(1) A survey of users by CVP and published as 'Pulmonary Function Testing: Art and Science' in the May/June issue, 1975.

(2) A survey of attendees at the Annual Seminar of Colorado Society of Cardiopulmonary Technologists, Denver, September, 1976.

(3) Proposed Automated Pulmonary Function Testing System (APUFS) by the Tri-Service Pulmonary Physiology Group in 1976.

Of the six hospitals surveyed, Fitzsimmons, National Asthma and National Jewish Hospitals are involved in both clinical and research areas of Respiratory Care while the last three hospitals use their labs for clinical purposes only. The following table gives an overview of the equipment and methods used in these labs. The detailed test procedures have not been included here but have been extensively used in selecting test parameters.

	FITZSIMMONS	NATL ASTHMA	NATL JEWISH	GENL ROSE	DENVER ROSE	SCOTT & WHITE
I. SPIROMETRY: DEVICE	WATER	DRY ROLLING SEAL	WEDGE	WATER	WEDGE	WEDGE
	(COLLINS)	(OHIO)	(MEDSCIENCE)	(COLLINS)	(MEDSCIENCE)	
VOLUME/CAPACITIES	X		X	X	X	
VC (SLOW)	X	X	X	X	X	X
FEVC/FIVC	X	X	X	X	X	X
FLOW/VOLUME LOOP	X	X	X	X	X	X
II. BODY PLETHYSMOGRAPHY: DEVICE		(COLLINS)	(COLLINS)			(COLLINS)
PROCEDURE	X	X	X			X
III. HELIUM DILUTION PROCEDURE	X	X	X	X	X	
IV. N_2 WASHOUT DEVICE			NITROVERTER(HP)			X
PROCEDURE	X	X	X	X		
V. GAS ANALYSIS: DEVICE	(PERKIN-ELMER)	(PERKIN-ELMER)	ABC-1			
BLOOD GAS/pH (OFF-LINE)	X	X	X	X		X
RESPIRATORY	X					
VI. EXERCISE TESTING: DEVICE		(COLLINS)	(COLLINS)			
PROCEDURE	X	X	X		X	X
VII. SYSTEM	COMPUTERIZED PDP 11	COMPUTERIZED (BIOLOGICS) NOVA	COMPUTERIZED (BIOLOGICS) NOVA	COMPUTERIZED		COMPUTERIZED PDP 11

Following is the summary of procedures used by seven medical directors and technicians in pulmonary function labs surveyed by CVP:

VC	7	RV	3
FVC	6	ERV	3
FEVt	5	FRC	4
PF	2	TLC	3
FEF 25-75	3	RV/TLC	1
FEF 200-1200	3	DLCO	2
MEFR	3	SB N_2 WASH	3
MVV	2	MB N_2 WASH	2
FLOW/VOL. LOOP	3	BODY PLETHY.	1

It should be noted that the above test parameters were the only ones in the questionairre.

APPENDIX D

PRODUCT SURVEY

The following are the major manufacturers who market pulmonary function laboratory products:

1. Cardio-pulmonary Instruments (G.D. Searle)

Pulmo-lab Model	5300	$12,525
	5000	$ 6,085
	5200	$ 9,875
	1100 (Water Spiro)	$ 3,368
	1200 (C.V.)	$ 5,318
Econo-lab.	4100 (He)	$ 6,145
	4200 (N_2)	$ 7,995

2. Collins, W.E.

Computerized Lung Analyzer P-1200 $20,000

3. Hewlett Packard

Pulm. Calculator System No. 47804A/47802A
Single Breath Diffusion 47404A
Pulm. Fcn. Analyzer 47402A
Pulm. Comp System 47801A

4. Life Science Equipment

Vanguard 500 DS Preprogrammed PFT computer ≃ $7K

5. Medistor (Terra Tech)

Pulm. Function Analyzer ≃$12K

6. Medscience

Pulmonizer System
Floop (Flow/Vol. loop)

7. Monaghan (Sandoz)

403 PFA

8. Ohio Medical (AIRCO)

   Omni-Lab System

9. Puritan Bennett

   Remac 360 Respiratory Measurements and Comparisons System

10. Beckman Instruments: PF 31 Ultrasonic Spirometer System $5,900

11. Other manufacturers and system houses:

    1. AMS
    2. Bio Cybernetics
    3. Bio Logics (Computer System only)
    4. CPFT
    5. DEC (Computer System Only)
    6. Jones Medical
    7. Siemens

TABLE D I COMMERCIALLY AVAILABLE PULMONARY FUNCTION TEST SYSTEMS.

	403 PFA (MONAGHAN)	PFA (MEDISTOR)	REMAC 360 (PURITEN-BENNET)	VANGUARD 500 (LIFE SUPPORT)	OMNI LAB (OHIO MED)	PULMO LAB (CPI) 5300	P-1200 (W.E. COLLINS)	4702A 47804A (HP)	PF31 (BECKMAN)
TYPE OF SYSTEM	SCREENING	SMALL	MEDIUM	MEDIUM	LARGE	LARGE	LARGE	EXPANDABLE TO LARGE	SMALL
PROCESSOR	NONE	NONE			MICRO-PROCESSOR			HP9825A PROG. CALCULATOR w/6.8 BYTE	
SPIROMETRY DEVICE	THERMISTOR	FLEISCH PNEU. #3	FLEISCH PNEU. #3	DIGITAL SPIRO w/STRAIN GAUGE	DRY ROLLING SEAL	DRY ROLLING SEAL #220	WATER BELL	PNEUMOTACHS (5 UNITS)	ULTRASONIC
TEST PERFORMED									
SPIROGRAM	NO	X	NO	TV & VC	X	X	X		X
FEVC	X	X	X	X	X	X	X	X	X
FIVC		NO		NO	X		X	X	X
FLOW-VOLUME	NO	NO	X	NO	X	X	X	X	X
SINGLE BREATH N_2 WASHOUT	NO	NO	X	NO	X	X	X	X	NO
MULTIPLE BREATH N_2 washout	NO	NO	X	NO	X	X	X	X	NO
He DILUTION	NO	NO	NO	NO			X		NO
RESISTANCE/COMPL.		NO	NO	NO	X	NO		X(8816A)	NO
DIFFUSION CAP.	X	NO	NO	NO	X	NO	X	X(47404A)	NO
BLOOD GAS	NO	NO	NO	NO	NO	NO	NO	NO	NO

TABLE D I CONTINUED

	403 PFA	PFA	REMAC 360	VANGUARD 500	OMNI-LAB	PULMO-LAB	P-1200	47804A	PF-31
RECORDING DEVICE			X-Y RECORDER DIGITAL PRINTER	ANALOG PRINTER (THERMAL STYLUS) $700 DIGITAL CARD PRINTER $1400	X-Y-T RECORDER DIGITAL STRIP PRINTER			THERMAL PRINTER(9066B) DIGITAL X-Y PLOTTER (9862A)	X-Y-T RECORDER
PREDICTED VALUE	NO (CHART)	X	X	NO (SLIDE RULE)	X		X	X	NO
PRICE				≈ $6,900 to $7,200		$12,525	≈ $20,000 ('72 PRICE)		$5,900
SPECIAL FEATURE(S)					PATIENT/ OPER. DISPLAY PANEL				

TABLE D II. COMMERCIALLY AVAILABLE SPIROMETRY DEVICES

	VANGUARD 500 (LSE)	OMNI-LAB (OHIO)	REMAC 360 (PUR-BEN)	PFA (MEDISTOR)	403 PFA (MONAGHAN)	(COLLINS)	47804A (H-P)	PULMO-LAB (CPI)
SPIROMETRY DEVICE	DIGITAL SPIRO w/STRAIN GAUGE	DRY ROLLING SEAL	FLEISCH PNEU. #3	FLEISCH PNEU #3	THERMISTOR	WATER	PNEUMOTACH 47303A (5 UNITS)	DRY ROLLING SEAL #220
RANGES:								
FLOW	0.01-12L/SEC		±10L./SEC		0-400 L./MIN 20-800 L./MIN		.05-10L/SEC	
VOLUME	> 0-9L.		±10L.		0-10L.	8 L.		
DYNAMIC								
ACCURACY:							±4.5%	
VOLUME	WITHIN 2.5% OF READING FOR MEASURED ±1 LSD. WITHIN 1 LSD FOR CALC. PARA-METER	2.5% or 100 mL. WHICH-EVER IS GR. 2.5% OR 10 L/MIN WHICH-EVER IS GREATER	±5%	1% OF F.S.	±5% OF COLLIN	±1%	ABSOLUTE	1% FS + FLOW ERROR
FLOW			±10%					1% FS
RATIO			±3%					
RESPONSE TIME	< 10 MSEC				<10 MSEC		10 MS TO 67% OF FINAL VALUE	
REPEATABILITY	CORRECTED TO BTPS WITHIN 2.5%				±2%			±5 mL.
STABILIZATION	> 3 MIN		30 MIN					1% F.S. IN 15 MIN.
TEMP. EFFECT					1% PER 3°F		< .05% OF READING/°C	
BACK PRESSURE	1.2 CM H_2O at 4L/SEC		1.5 CM H_2O/L./SEC	1.2 CM H_2O @ 4L./SEC	1.0 CM H_2O @ 100 L/M .03 CM 8.0 CM H_2O @ 500 L/M H2O/L/SEC			
FREQUENCY RESPONSE			DC TO 10 HZ					3 db DOWN AT 50 CPS
DEADSPACE				160 mL.				
TRIGGERING LEVEL	TURN ON: .3 L/SEC OFF:.01 L/SEC	< .2L/SEC	.2L./SEC					
CALIBRATION			EVERY 90 DAYS					

TABLE D III

GAS ANALYSIS SYSTEMS CURRENTLY AVAILABLE

	BLOOD	GAS IN VIVO	TISSUE	RESPIR	pH	ANESTH.	PRICE
PERKIN ELMER (MGA 1100AB)	X	X		X			
SRI (G.D. SEARLE) (MEDSPECT MS8)	X	X		X		X	≃ $18,000
BENDIX (QUAD M.S.)	X			X			
FINNIGAN (RESP. GAS ANAL)				X			≃ $10,000
MCGRAW RESP. THER.							
VARIAN ASSOC.							
BECKMAN 160 PGA	X			X			
STATHAM (M.S.)	X		X	X			≃ $17,000
TECHNICON (B.G. ANALYZER)	X	X					
VACUMETRICS (RMS-BG; MMS-100)				X			≃ $22,000
CVC PRODUCTS (MA-3A)	X	X		X		X	

The following are some of the stand-alone medical gas analyzers available in the market:

1. CPI (Searle) Model 410 Nitrogen Analyzer

   Accuracy: ±1% fs or ±2% reading to 85% of scale. (whichever is less)

   Range: 0 - 100% N_2

   Response Time: < 30 msec.

   Price: $2700 w/Digital Meter.

2. Hewlett-Packard: Model 47302A Nitrogen Analyzer

   Accuracy: 0.2% fs for 0-10% range

   0.5% fs or 1% reading for 10-90% range

   Response Time: < 50 msec

3. Med-Science: Nitralyzer

   Accuracy: ±1% f.s., ± .2% N_2

   Response Time: ≃ 50 msec.

4. Beckman Instruments: Model OM-11 Oxygen Analyzer

   Range: 0-100% O_2

   Resolution: 0.5% O_2.

   Price: $3900.

   Model LB-2 Medical Gas Analyzer (Nondispersive Infrared Instrument)

   Measures: CO_2 (0-10%), N_2O (0-100%)

   Halothane (0-3%) CO (0-0.1%, 0-0.3%)

   Price: $3600 + $3300 (digital display, vacuum pump and peak detector).

5. Med-Science: Helialyzer. (Thermal Conductivity Type)

   Range: 0 - 5%; 0-15% He.

   Linearity: ±2% He.

   Sensitivity: 0.02% He.

   Response Time: 8 sec. 92% FSD.

APPENDIX II

CARDIAC OUTPUT CALCULATIONS

This appendix contains the specifications for software programs for calculating cardiac output by:

(a) Thermal Dilution Technique, and

(b) Dye Dilution Technique.

They were intended for implementation on the CP 1600 microprocessor as part of the MEDDARS 300 Cardiac Catheterization Application Software package. The report appears in the format in which it was submitted to TID.

Honeywell Interoffice Correspondence

Date: June 28, 1977

cc. A. Sheth - 255
T. Stuebe - 255

To: Stan Edwards - 215

From: Ron West - 255

Location: TID - Denver

Subject: MEDDARS SERIES 300 THERMAL DILUTION FEATURE

D. Sengupta has expanded the MEDDARS Series 300 thermal dilution specification to a detailed functional document, The master schedule calls for engineering to complete this software by December. This program will hopefully share many routines with the Dye Curve program schedule for completion at the end of August.

Therefore I would appreciate it, if marketing would review the attached document and approve it for implementation. A similar document on the Dye Curve program is in typing and will be forwarded as soon as possible.

Deb's review indicated that appearance time and mean transit time are not being computed from thermal dilution curves on other available systems. It isn't clear why not. Any insight you have or may be able to obtain on this specific feature would be very useful.

R. E. West

RW/mhf
attachment

THERMAL DILUTION CALCULATION REQUIREMENTS:

The following is the functional specifications for the Meddars 300 software implementation of the Thermal Dilution procedure. In this technique for determination of cardiac output, a bolus of cold fluid is injected into the central circulation before the right or the left side of the heart and the resultant change in temperature is measured in the pulmonary artery or the aorta. The following assumptions have been made:

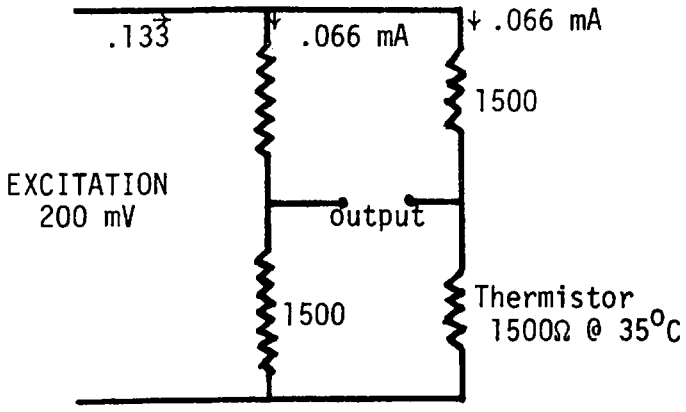
1. The temperature is measured during the procedure at only the sampling site and not at both the injection and sampling sites. Several recent papers on the subject suggest that for greater accuracy in determination of the injectate temperature, the injection site temperature should also be measured for the duration of the injection. The cardiac output equation included here has a correction factor to account for the rise in injectate temperature. If a thermistor is present at the injection site, this corrected factor is eliminated, and instead, this thermistor has to be calibrated and its signal has to be sampled and integrated for the duration of the injection to calculate the mean injectate temperature.

2. The calibration points for the sampling site thermistor are assumed to be 35^{o} and $40^{o}C$. While these are the suggested calibration points by several manufacturers, some others suggest the use of 34^{o} and $38^{o}C$.

3. It is suggested that the area under the temperature profile curve be calculated by extrapolating the initial downward slope of the thermal output response curve expenentially to the baseline temperature. This gives the most accurate results and the numerical technique is the same as that required to calculate the dye dilution curve area. However, the area is frequently calculated up to the point where the temperature reaches 5% of the peak value of the curve. However, this latter method is reasonably accurate since there is very little recirculation occurring during thermal dilution maneuver.

Thermistor Bridge Analysis:

Usual thermistor probes have a resistance of about 1500 ohms at 35°. (Typical Values: Roche probe 1512 ohms at 35°C and Swan-Gatz Series 400 has 1472 ohms at 35°C). In order to avoid self-heating of the probe, it is required that the maximum voltage applied across the probe should not exceed about 100 mV.



Total Current under balance

$$= \frac{200 \text{ mV}}{1500\ \Omega} = 0.133 \text{ mA}$$

For thermistor w/1500 ohms at 35°C, we have 42.86 ohms change per °C. Assuming resting blood temperature at 37°C,

Output for resting blood at 37°C, where thermistor resistance is 1585.7 ohms is

$$100 - \frac{1585.7}{3085.7} \times 200 = -2.78$$

If the temperature drops now during test to 36°C, the thermistor resistance will be 1542.85 ohms and output of bridge = $100 - \frac{1542.85}{3042.85} = -1.4$ mV.

Therefore, maximum excursion of voltage during the procedure is from -1.4 mV to -2.78 mV.

If the Interface Module is used to introduce the temperature data into the Meddars system, it will be necessary to preamplify the signal before it enters the module.

CALIBRATION (of the thermistor at sampling site)

```
SEND 35 DEGREES CENTIGRADE
END TO SAMPLE?
                XXXX A/D COUNTS
SEND 40 DEGREES CENTIGRADE
END TO SAMPLE?
                XXXX A/D COUNTS
```

The change in A/D counts for 1^{o} change in temperature

$$= \frac{(\text{A/D COUNTS AT } 40^{o} - \text{A/D COUNTS AT } 35^{o}\text{C})}{5}$$

This value can be adjusted by changing the gain of the thermistor bridge output. It should be set so that the test results have adequate accuracy. A normal thermal dilution curve (assuming an injectate volume of 10cc) has a temperature variation of 0.6^{o} - 1.5^{o}C, depending on the location of the injection and sampling catheters.

TEST PROCEDURE:

```
INJECTION SITE CATH NO.?
SAMPLING SITE CATH NO.?
```

These should be available as a list, with the operator selecting the correct numbers. The injection sites are usually (a) left atrium, (b) right atrium, (c) distal pulmonary artery, and the sampling sites are usually (a) pulmonary artery, and (b) aorta.

```
INJECTATE TYPE NO.?
```

Three types of injectates are usually used and should be available in a list for operator selection. They are: (a) saline, (b) D5W and (c) patient blood.

```
ENTER INJECTATE TEMP. IN CENTIGRADE
```

This temperature is usually between 0^{o} and 5^{o}C, although a few labs use injectate at room temperature.

ENTER INJECTATE VOLUME IN MILLILITERS

This volume is usually 3 to 10 mL. After all the above data has been recorded, the injectate can be introduced. The injection period is usually 0.1 seconds and after a finite propagation delay known as the appearance time, the temperature at the sampling starts falling from the resting blood temperature to a minimum, and then rises back again to the resting blood temperature as the injectate passes on. There is very little recirculation that can be noticed when using this procedure, and the curve usually drops to about 2-3% of its peak value within 15-20 seconds after injection. The typical excursion of temperature at the sampling site is about $0.6^{o}C$ to $1.5^{o}C$ from the resting blood temperature. The maximum computation time typically never exceeds 50 seconds.

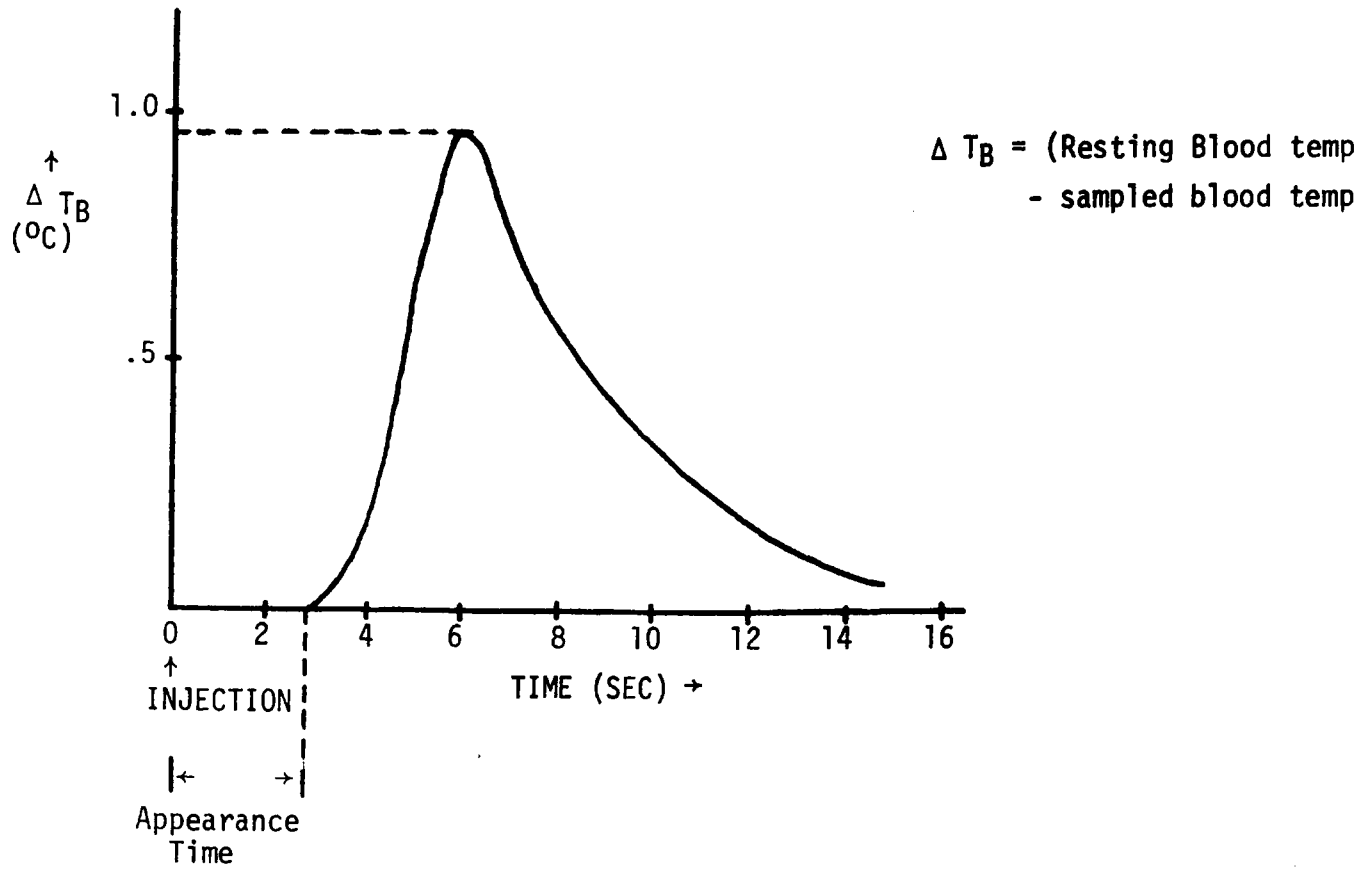


FIGURE 1: TYPICAL THERMAL DILUTION CURVE

The cardiac output, CO, in mL/min, is

$$= \frac{(BDT - IJT) \times IJV \times SGSH \times CF \times 60}{\text{Area of temp-time curve}},$$

where

BDT = blood temperature in ^{o}C.

IJT = injectate temperature in ^{o}C.

IJV = injectate volume in mL.

$$SGSH = \frac{(\text{Sp heat} \times \text{Sp gravity})\ \text{injectate}}{(\text{Sp heat} \times \text{Sp gravity})\ \text{blood}} = \begin{array}{l} 1.06 \text{ for D5W} \\ 1.08 \text{ for saline} \\ 1.00 \text{ for blood} \end{array}$$

CF = Heat loss correction factor for injectate temperature rise = 0.825/sec.

Area of curve = $\int_{t=0}^{\infty} \Delta T_B \, dt$ and can be calculated by a procedure identical to that for dye dilution. The curve is extrapolated to the baseline temperature from the initial downslope and the area under the curve calculated. An alternate method would be to calculate the area till the temperature drops to 5% of the peak.

The other parameter calculated is the Cardiac Index. CI = C.O./Body surface area.

The graphical representation is for temperature variation of blood from its initial resting volume, plotted against time. Usually the temperature change is shown as a positive value. A few systems also present the appearance time which is the time between the injection and the initial change in temperature from baseline ($0.05^{o}C$ from resting blood temperature). Since the appearance time is an important parameter to identify possible shunts, it is suggested that this parameter be calculated.

A typical final data record is shown in Figure 2.

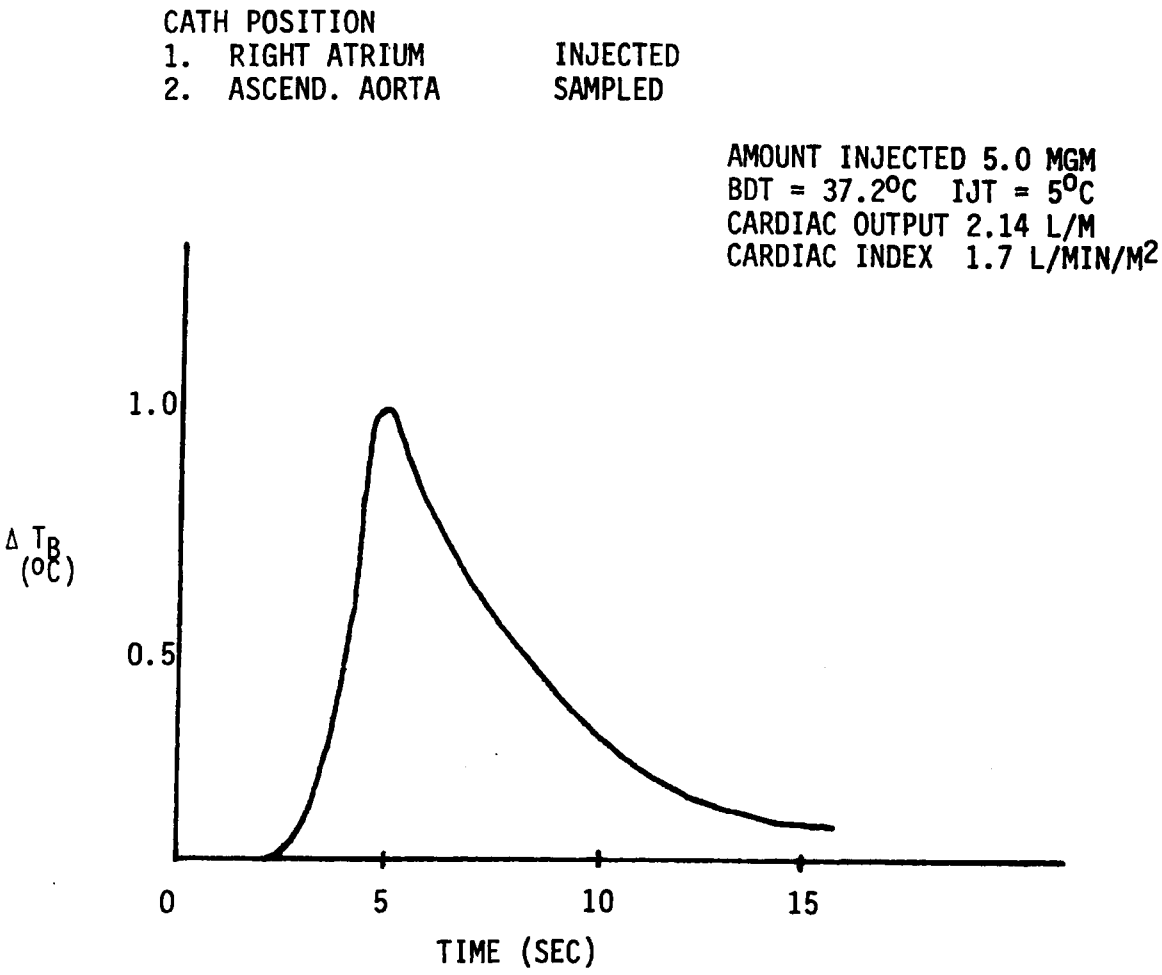


FIGURE 2: OUTPUT FORMAT

DYE DILUTION CALCULATION REQUIREMENTS

The following is the functional specifications for MEDDARS 300 software implementation of the Dye Dilution procedure. In this technique for determination of Cardiac Output, an opaque dye (cardiogreen) is introduced into the cardiovascular system at an injection site and then the concentration of dye is measured as a function of time at a downstream sampling site. The dye concentration is measured by a densitometer which is a photo-electric device with an output analog signal proportional to the dye concentration.

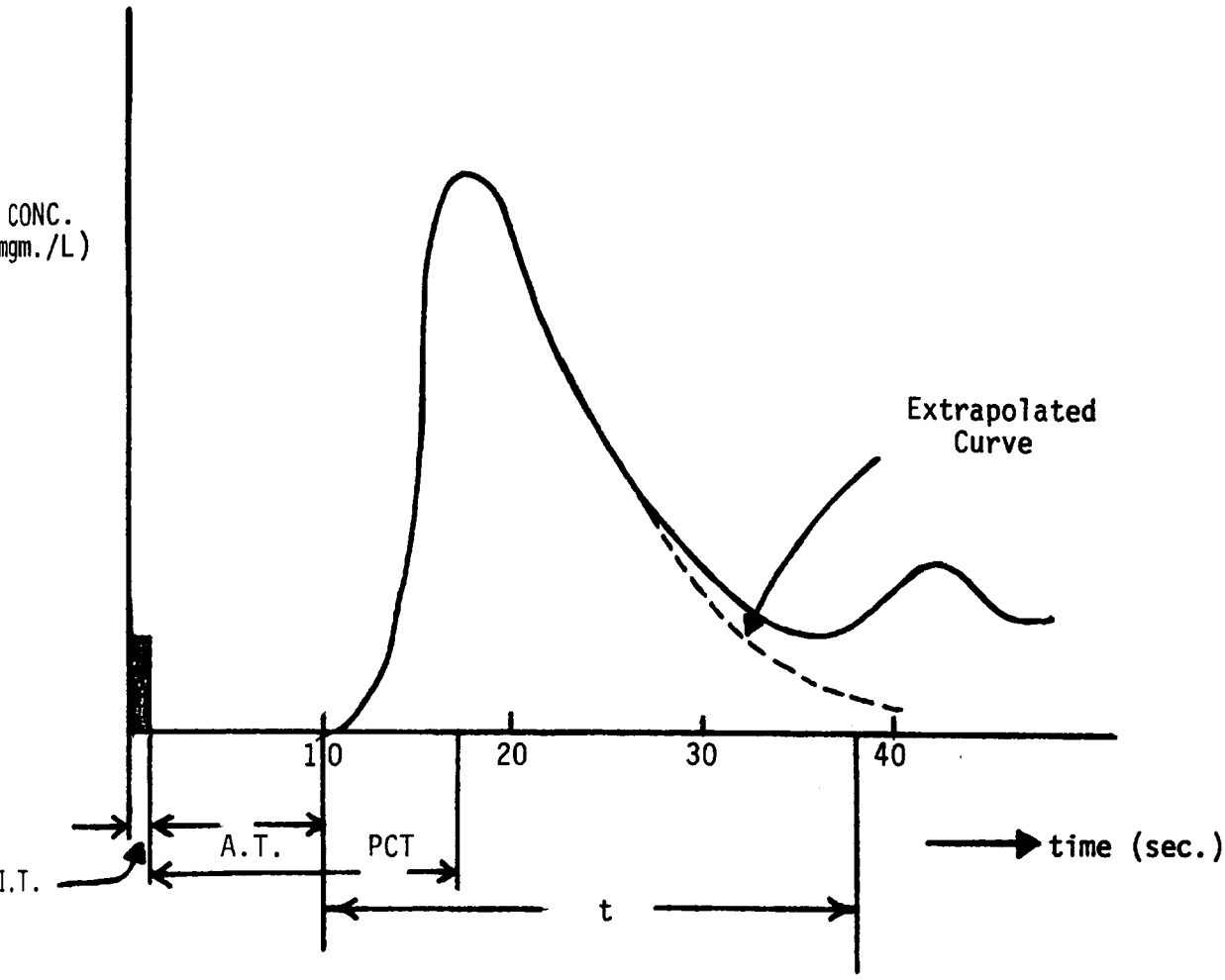
The data in this procedure has to be sampled in three phases:

(a) baseline data to establish the baseline for the densitometer output. The output for this phase is obtained when the patient's blood sample without dye is drawn thru the densitometer.

(b) calibration data to establish the calibration factor. This is done by mixing thoroughly a known amount of dye with a known volume of patient's blood and passing the mixture thru a densitometer. The data is sampled for a fixed duration (5 seconds) and its average is used to determine the calibration factor.

(c) actual test data has to be sampled for a fixed duration of time which is usually of the order of 35-40 seconds.

A typical dye curve is illustrated in figure 1. The typical injection sites are the pulmonary artery, left atrium and the left ventricle and the sampling sites are left atrium, aorta and the femoral or brachial artery. However under special circumstances other sites are used for injection and sampling.



IT - Injection Time

AT - Appearance Time

PCT - Time for appearance of peak concentration

t - Passage Time.

FIGURE 1 : TYPICAL DYE DILUTION CURVE

In the bolus injection technique, a known amount of dye is mixed with blood or saline solution and quickly introduced into the injection site. The operator must indicate to the system when the injection starts and ends. However with automatic dye injectors it is difficult to get these two points as they occur a second or so apart. The time between end of injection and first appearance of the dye at the sampling site is know as the appearance time and is about 5 to 10 seconds. It is a function of the distance between the injection and sampling site. There can be appreciable error in its measurement due to passage time thru the injection catheter.

The dye then appears at the sampling site and is withdrawn with the help of a pump to the cuvette of a densitometer which measures the concentration of the dye in the blood sample. This dye concentration rises rapidly to a peak and then starts faiiling exponentially till recirculated dye starts interacting with the original dye at the sampling site, causing the concentration time curve to rise again. It is possible to extrapolate the exponential portion of the first curve to the baseline and thereby eliminate the effect of recirculation from the calculations. The initial waveform usually persists for 15-25 seconds after first appearance of waveform. Therefore the test data must be sampled for about 35-40 seconds for adults and 10-15 seconds for children. H.P. and Waters sample the date for 35 seconds, and displays the curve upto that point of time.

Normally, densitometers have a full scale output of 50-250 millivolts and usually have output gain control potentiometers.

CALIBRATION (of densitometer output)

SEND BASELINE OUTPUT
CALIBRATION AMOUNT OF DYE, MGM/MLS.
SEND CALIBRATION OUTPUT, VOLTS

The signal is sampled for 5 seconds, and its mean is calculated for the average value for calibration output.

$$\text{Calibration factor} = \frac{\text{(Calibration Output) - (Baseline Output)}}{\text{(Amt of dye/total volume)}}$$

TEST PROCEDURE:

INJECTION SITE CATH NO. ?
SAMPLING SITE CATH NO. ?

These should be available as a list, with the operator selecting the correct numbers. The typical injection sites are the (a) pulmonary artery, (b) left atrium, and, (c) left ventricle and the usual samples sites are (a) left atrium, (b) aorta, and (c) the systemic artery.

ENTER AMOUNT OF DYE IN MGMS
ENTER INJECTATE VOLUME IN MILLILITERS

This volume is usually 5 to 10 mL. After all these above data has been introduced into the system, the operator can start injecting the dye. The operator should inform the system when the injection begins and ends so that data sampling can begin.

For adults the data should be sampled for about 40 seconds with a sampling rate of about 20 per second for a total of 800 sampled points. It should be sampled for a shorter period for pediatric cases.

The cardiac output, in mL./min., is

$$= \frac{I \times 60 \times \text{Calibration Factor}}{\text{Curve area under first circulation}}$$

$$= \frac{\text{mg.} \times 60 \times \text{V/mg/mL}}{\text{Volts} \times \text{Seconds}} \text{ mL./min.}$$

where I = amount of dye injected in milligrams and curve area = area under the dye concentration - time curve.

The curve area can be calculated by simple integration once the downward exponential decay curve has been extrapolated to the baseline to eliminate recirculation. The Stewart Hamilton's method is considered the standard extrapolation method and yet it is seldom implemented in commercial systems due to its complexity. Therefore some modified version of the S-H technique is utilized by most systems.

The method suggested for use here is a modified Steward Hamilton technique. The mathematical justification for the method appears later.

1. Identify the peak concentration.
2. Calculate the 75% and 45.5% of peak value and mark points $Y1$, and Y_2 at time t_1 and t_2 which have those concentration values.
3. Calculate time constant $\tau = 2 (t_2 - t_1)$.
4. Calculate Y_3, Y_4, Y_5, Y_6 values and plot these points at time τ, 2τ, 3τ, 4τ away from t_1.
5. Calculate area upto point Y_1, by summation of instantaneous values. Area of remaining curve is = $(Y_1 . \tau)$. Add the two areas to give the total.

   Total Area = Summed area upto Y_1 + 0.75 A τ.

CATH POSITION

1.	PULM ARTERY	INJECTED
2.	AORTA	SAMPLE

AMOUNT INJECTED = 4.5 MGM.
A.T. = 7.5 SEC. PCT = 13.0 SEC.
CARDIAC OUTPUT = 3 L./MIN
CARDIAC INDEX = 1.5 L./MIN/M2
MCT = 15.6 SEC. CBV = 0.78 L.

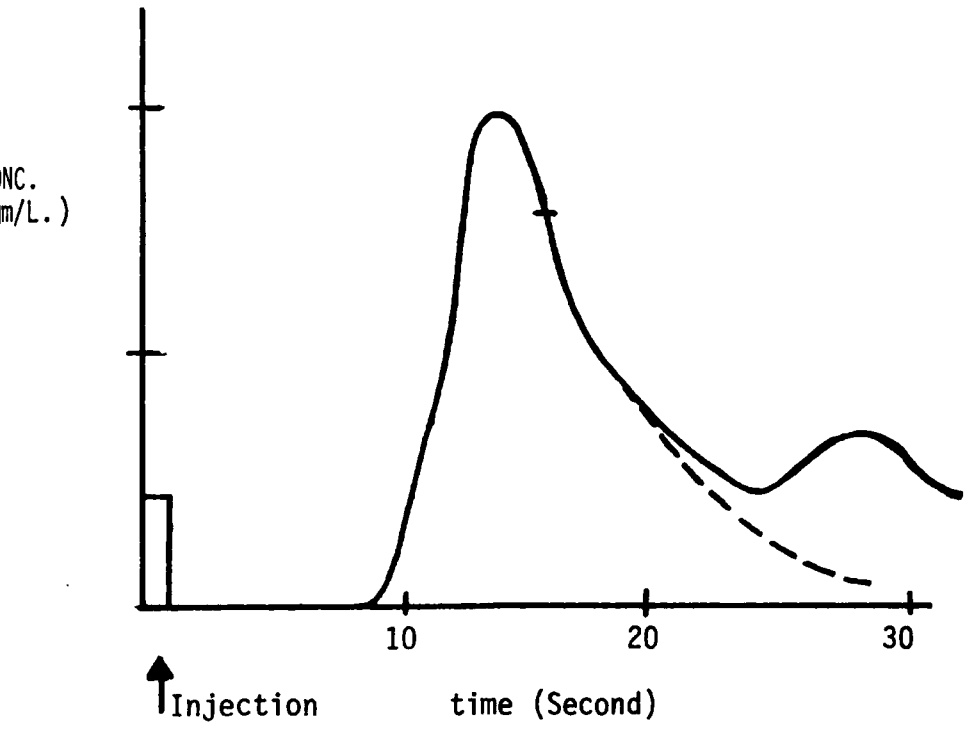


FIGURE 2: OUTPUT FORMAT

MATHEMATICAL BACKGROUND

The extrapolation of the downward exponential curve can be justified by the method outlined earlier if the following two assumptions are true:

1) the curve is exponential between the 75% and 45.5% concentration points,

2) recirculation does not start upto the point were the curve has dropped to 45.5% of peak concentration.

The equation for a first order decaying exponential is

$Y = Ae^{-t/\tau}$ where A is the initial value of the equation, in this case the peak concentration.

If Y_1 and Y_2 are two concentrations equal to 75% and 45.5% of peak concentration and occuring at time t_1 and t_2.

$$Y_1 = A\, e^{-t_1/\tau} = 0.75\, A$$

$$Y_2 = A\, e^{-t_2/\tau} = 0.455\, A$$

$$\frac{Y_1}{Y_2} = e^{-(t_1 - t_2)/\tau}$$

$$\ln\left(\frac{Y_1}{Y_2}\right) = (t_2 - t_1)/\tau$$

$$\tau = \frac{(t_2 - t_1)}{\ln\left(\frac{.75A}{.455A}\right)} = \frac{(t_2 - t_1)}{.5} = 2\,(t_2 - t_1)$$

Therefore from the values of t_1 and t_2, the time constant τ can be calculated. Now the points on the exponential curve have to be calculated for display.

Starting from the 75% A point as the beginning point of the exponential curve,

At $t_3 = t_1 + \tau$, $Y_3 = Y_1 e^{-\tau/\tau} = A(0.75\ e^{-1}) = .276\ A$

$t_4 = t_1 + 2\tau$, $Y4 = Y_1 e^{-2\tau/\tau} = A\ (0.75\ e^{-2}) = .101\ A$

$t_5 = t_1 + 3\tau$, $Y_5 = Y_1 e^{-3\tau/\tau} = A\ (0.75\ e^{-3}) = .037\ A$

$t_6 = t_1 + 4\tau$, $Y_6 = Y_1 e^{-4\tau/\tau} = A\ (0.75\ e^{-4}) = .014\ A$

Points Y_3, Y_4, Y_5, Y_6 can be plotted τseconds apart after t_1, to give the extrapolated curve.

The area upto Y_1, where concentration is 0.75 peak, can be calculated by point by point summation. The area of the rest of the exponentially decaying curve is

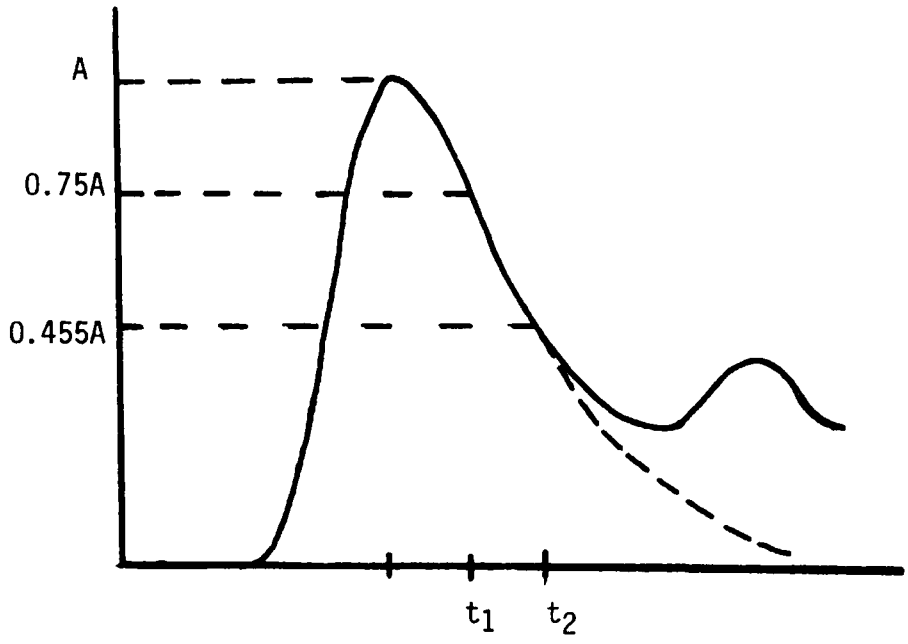
$$\text{area} = \int_0^{\infty} 0.75\ A\ e^{-t/\tau}\ dt$$

$$= 0.75\ A\ \left| - \tau e^{-t/\tau} \right|_0^{\infty}$$

$$= 0.75\ A\ (- \tau e^{-\infty/\tau} + \tau e^{-0/\tau})$$

$$= .075\ A\ (\ 0 + \tau\ ) = -.75\ A\ \tau$$

Total area = Summed Area upto Y_1 + 0.75 A τ.



MCT is the average time taken for the particles to travel from the injection point to the sampling point. This also means that MCT seconds after injection of dye, half the particles have reached the sampling site. The total summed area under the curve is also a measure of the total number of dye particles reaching the sampling site. Therefore when summed area is equal to half the total, half the particles will have reached the sampling site and the time elapsed after injection is MCT.

MCT = Time after injection where area is half of total and the area is calculated as

$$C_1t_1 + C_2t2 + ...$$

The only conceivable problem would be if the point occurs after t_2 because the curve here is extrapolated and their values are known are τ seconds apart (due to an attempt to avoid exponential calculations) and not available sampling period apart. But it can be shown that half the area is covered before t_2.

Considering an exponential curve from the peak, on the downward slope,

Area upto t_2 where concentration is 0.455 peak,

$$= \int_0^{t_2} Ae^{-t/\tau}\, dt$$

$$= A \left| -\tau e^{-t/\tau} \right|_0^{t_2} = A\left(-\tau e^{-t_2/\tau} + \tau e^{-0/\tau}\right)$$

$$= A\tau - A\tau e^{-t_2/\tau}$$

Now $0.455\, A = A\, e^{-t_2/\tau}$

$$\ln(.455) = -\frac{t_2}{\tau}$$

$$-t_2 = +\frac{\tau}{\ln(.455)} = -1.27\,\tau$$

$$\text{Area} = A\,\tau(1 - e^{-1.27})$$

$$= A\,\tau(1 - .28) = 0.72\,A\tau$$

Therefore only 28% of the area for the downward slope is left after t_2, and the half of total area will definitely occur before t_2.

TYPICAL VALUES

Withdrawal Systems (Commercially Available):

Needle 19 gauge

Catheter French No. 7, 70-100 cm;

Internal Volume = 1.2 to 2.4 mL.

Pump (typical)

Max. flow rate 60 cc/minutes

Max. withdrawl time 45-72 seconds

Max. reservoir volume 50 c.c.

The withdrawal rates are determined by the characteristics of the densitometers used and is usually between 15-25 mL/min.

Densitometer (typical)

Cuvette flow rates 5-40 mL./min

lumen volume 0.02-0.03 mL.

Output levels 50-250 mV.

It is suggested that the most satisfactory withdrawal system should meet the following:

$$\frac{\text{Catheter Volume (c.c.)}}{2 \times \text{Withdrawal Rate (c.c./sec,)}} < \text{R-R interval/sec.}$$

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VITA

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