This report describes the current status and application of the biplane video roentgen densitometry, videometry and video digitization systems. These techniques have been developed, and continue to be developed in this laboratory for studies of the effects of gravitational and inertial forces on cardiovascular and respiratory dynamics in intact animals and man.

A list of papers, published or in preparation since the last progress report (October 1, 1972) stemming from research work supported by this grant, is appended to this report.

Progress over the past six months has been particularly in the field of lung dynamics and three-dimensional reconstruction of the dynamic thoracic contents from roentgen video images. It is anticipated that these data will provide added insight into the role of shape and internal spatial relationships (which is altered particularly by acceleration and position of the body) of these organs as an indication of their functional status.

Erik L. Ritman, M.B.
for
Earl H. Wood, M.D., Ph.D.
Determination of Volume Changes in Any Cardiac Chamber Without Quantitative Calibration of the Video Roentgen System

Objective measurements of the amount of contrast medium in selected parts of the circulation can be obtained with roentgen videodensitometry (Sturm and Wood, 1971). Indicator dilution curves can be recorded using a videodensitometric sampling window which covers the entire silhouette of a cardiac chamber (Bursch, Heintzen, and Simon, 1972). These curves represent changes in the entire amount of indicator in the heart chamber under study. Provided the entry of the amount of contrast medium into the heart chamber, as well as the following fractional ejection occur in proportion to the blood flow, the resulting density curves can be used to calculate continuously (60 times per sec) the volume of the cardiac chamber.

Linearity of the densitometric recording system with respect to the amount of contrast medium transradiated requires a high-fidelity logarithmic amplification of the video signal prior to processing of the signal by the conventional videodensitometric circuit. Linearity of the system has been proven by x-ray density measurements in model experiments. Automated analysis of the digital representation of the radiopaque dilution curves is provided by computer processing. The program identifies and eliminates the cyclic non-specific density changes in roentgen opacity resulting from changes in shape and position of the heart. This is achieved by sampling the video roentgen image before the contrast medium is injected into the circulation. Subsequent calculations based on the oscillation of the indicator curve (which has been suitably corrected for the non-angiographic opacity changes) produces values which represent continuous changes of blood volume in the heart chamber (e.g., left ventricle) during one or more heart cycles. Another program displayed the derived densitometric values in conjunction with blood pressures, blood flow as well as values of left ventricular volume calculated by roentgen videometry.

Application of the densitometric method for volume measurement is of interest because no assumptions need be made concerning specific geometrical shapes of the heart chamber and no absolute calibration is required for determination of ejection fractions. This technique is particularly applicable for determination of volumes of the left atrium or even the right ventricle because there is no need to assume a shape for the chamber. This technique is used to provide on-line real-time display of left ventricular volume change during experiments. This has permitted immediate assessment of the impact of an omitted atrial stimulus on ventricular filling in the intact anesthetized dog.

Determination of the Shape and Dimension of Objects from Biplane Roentgenographic Data

Accurate measurement and reconstruction of the endocardial and epicardial surfaces of the left ventricle and other heart chambers is necessary for meaningful
interpretation of the dynamic shapes, and rates of change of motion of the myocardium, and perhaps eventually to the calculation of regional myocardial stress-strain relationships as well.

Procedures which employ multiple view, rather than simply biplane data, are complex because of their higher information content. Fourier Transforms of multiple density profiles, and algebraic reconstruction techniques show great promise for high resolution reconstruction of the very irregular cross-sections.

Present methods of calculating the volume and dimensions of the left ventricular cavity by means of left ventricular angiography all presuppose some form of elliptical shape for this chamber. The data used for these calculations are obtained from one or at most two angiographic silhouettes of the left ventricle. However, it has been demonstrated in this laboratory and elsewhere that the relatively simple problem of reconstructing the shape of an elliptical disc cannot be solved unambiguously from two projections of this disc recorded in planes perpendicular to the surface.

It follows that the actual shape and dimensions of the left ventricle cannot be determined by conventional multiple plane angiography, no matter how many silhouettes obtained from an infinite number of views around the long axis of the ventricle are used, or the number of cross-sectional dimensions of the resulting infinite number of multiple silhouettes of this chamber which are measured.
Cross-sectional reconstruction from multiview roentgenographic data requires that all structures in the cross-section always contribute to every projected image. This means that for reconstruction of the left ventricle, the entire cross-section of the chest at the level of the left ventricle must be present in every view of the ventricle. This requirement may be relaxed if the structure of interest has considerably higher roentgen absorption than the surrounding tissue. This is partially realized in angiography where the left ventricular chamber is extremely radiopaque relative to other tissue masses. This condition can be achieved however, if the "background" is subtracted, thereby leaving only the angiographically delineated image. This subtraction must be performed for each angle of view at "identical" phases of the cardiac cycle.

This figure illustrates the cross-sectional reconstruction of an excised heart filled with radiodense barium paste. The top photograph is an orthogonal radiograph of a transversely sliced section of the heart. The bottom photograph is a computer-generated plot of this transverse section reconstructed from multiple roentgen videographic views taken parallel to the plane of the cross-section.
The biplane reconstruction technique (see Figure 2) assumes uniform density of cardiac structures, and has much difficulty resolving internal objects such as the papillary muscles and trabecular invaginations of the endocardial wall. Superior procedures employ multiple view, rather than biplane data, but are more difficult to employ in cardiac reconstructions because of the dynamic nature of the information content. Planning for these procedures is considered next.

Reconstruction of the Shape of Three-Dimensional Objects from Multiple Radiation Transmission Density Profiles

Introduction

Early workers, using Fourier techniques, believed that use of projections spaced along a full 180° rotation was necessary for high-quality reconstruction. Our experience shows that this range of projections is desirable, but not necessary.

Changes to our biplane video system and utilizing our expanding means to digitize images has enabled us to use these techniques as a viable laboratory tool. The accurate reconstruction of the heart from projections is the first step in measuring spatial distribution of length-strain relationships over the full anatomic extent of the heart walls, 60 times per second. The ability to quantize small changes in local radiopacity will allow visualization and measurement of blood flow, ventilation, and mechanical displacements in the thorax.

Applications of Reconstruction in this Laboratory

Our laboratory is in a position to make several contributions to the field of cross-sectional reconstruction because of the available facilities and our experience with video techniques. Our present efforts may be listed as follows:

a. Development of a high temporal resolution single or biplane video cross-section camera. Our present video image-intensifier chain has been converted into a vector for digitizing cross-sections at a rate of 60 per second. The digitized data is analyzed at a later time to produce the reconstructed images.
Initial attempts at cross-sectional reconstruction of dynamic anatomic structures such as the heart have been achieved by use of the systems with the characteristics we have described. Our results to date indicate that sufficient accuracy can be achieved to justify the development of such a video cross-section camera.

b. Development of Cross-Section Reconstruction Algorithms

Our laboratory has developed contacts with several laboratories engaged in cross-section reconstruction. Dr. Gabor Herman has visited our laboratory and has contributed a copy of his reconstruction methods library which is known as SNARK. At present, no Fourier reconstruction algorithm is contained in SNARK nor is there any SNARK algorithm to accommodate the divergent field geometry common to focal spot x-ray sources used in medical x-ray systems.

A method has been developed in our laboratory to convert data taken in a divergent geometry into the corresponding data for a parallel geometry. We have written a noise tolerance limit, divergent geometry relaxation method algebraic reconstruction program which will operate as a subroutine to SNARK. The SNARK program has been implemented on our CDC 3600 computer. An example of a reconstructed cardiac cross-section is demonstrated in Figure 1.

Although cross-sections have been produced using ultrasound B-scan methods, it is possible to generate cross-sections with ultrasound by applying any of the reconstruction methods described previously. An apparatus for generating such pictures has been constructed. It consists of a U-shaped yoke on which are mounted two focused transducers at the ends of the two legs. These transducers are aligned such that their centers and focal points lie along a common line. The U-shaped piece is mounted on the arm of a nuclear scanning machine. A test object or biological specimen is mounted on a rotation device under water between the two transducers. Rotation of the object is coordinated with the scanning motion of the scanning arm so that transmission profiles are produced as a beam of ultrasound traverses the specimen between the transmitter transducer and the receiver transducer. Electrical signals from the receiver transducer are amplified logarithmically before being recorded on digital tape or digital disc for later analysis. The data produced may be analyzed using the subroutines contained in original SNARK since parallel projection geometry is employed.

Summary

Cross-sectional reconstruction from density profiles is a valuable new tool which will find increasing use in physiological research. The application of this tool to static anatomic structures has reached a high state of perfection
in a few years; applications to non-static structures requires the development of new devices and techniques. Nevertheless, with our present equipment and during the transitional period as our equipment is improved, ultrasound and dynamic roentgen cross-section pictures of high utility will be obtained.

Significance

It is our belief that perfection of techniques for accurate, rapid, three-dimensional analysis of the cardiac chambers of the functioning heart, or for that matter of other internal structures, will lead to an increased understanding of their functional nature in health and disease. In particular, accurate knowledge of 60-per-second changes in left ventricular volume coupled with a detailed knowledge of the moment-to-moment changes in the myocardial thickness and curvature over the entire extent of the left ventricle will aid in the measurement and comprehension of cardiac phenomena, such as local integrity of the myocardium, efficiency of myocardial contraction, and perhaps stress-strain relationships within the myocardial wall as well. Similarly, reconstruction of the thoracic cross-section will contribute considerably to our understanding of dynamic shape change of the lungs and heart under conditions of increased gravitational and inertial forces.

Left Ventricular Function as Determined From Left Ventricular Angiograms Performed in the Metabolically-Supported Isolated Left Ventricle

Aim

The primary function of the cardiac muscle cells is to generate the cyclic changes in length and tension in the myocardium required to generate the intrachamber pressures necessary to propel the requisite volumes of blood through its chambers. Basically therefore, direct studies of the functional status of the myocardium in the intact circulation requires development of methods capable of measuring the length and tension of the myocardial walls and their rates of change over as complete an anatomical extent of the cardiac chambers as possible and the full instant-to-instant temporal extent of individual cardiac cycles. With the video roentgen angiographic digital computer data acquisition and analysis chain in its current state, data acquisition and analysis from two physiological experimental protocols have been initiated.

This experimental series utilizes a completely isolated canine left ventricle supported by a separate coronary circulation. The ventricle is suspended at the intersection of two orthogonal x-ray beams, and the resulting biplane images were recorded on one videotape along with sixteen analog-data channels.

The left ventricle was surgically isolated and the right ventricle and atrium resected, as shown schematically in Figure 3.
SCHEMATIC OF SURGICALLY ISOLATED, METABOLICALLY SUPPORTED CANINE LEFT VENTRICLE
Separate Artificial Systemic and Coronary Circulations

Figure 3

This preparation permits complete control of left atrial pressure, aortic pressure, heart rate, as well as region of pacing by epicardial electrodes, coronary perfusion, and coronary perfusion of drugs. The pumped fluid is radiopaque so that continuous angiographic analysis can be performed under both steady and transient state conditions. Ventricular output is measured by ventriculography, cannulating flowmeter (aorta), and by volumetric collection just distal to the Starling Resistor.

This preparation is ideally suited for angiographic analysis of both the endocardial and epicardial silhouette shapes. It was stable as measured by the left ventricular pressure and stroke volume output. In one experiment, for example, the output of the ventricle, as measured by volumetric collection, was 750 to 1,000 ml/min, which would represent about 80 ml per kg body weight. The preparation remained stable over a sequence of eight hours and the stroke volume over periods of 10 to 15 seconds was reproducible to within 5%. Comparison of stroke volume, as calculated by ventriculography, matched closely over a range of stroke volumes from 2 to 12 ml.

Figure 4 is a plot of volumetrically determined stroke volume along the ordinate plotted against the videometrically determined stroke volume along the abscissa.
The ventricular volume is calculated from the 100 diameters in each biplane silhouette. Each data point represents the mean stroke volume calculated from a 20° to 30° continuous angiographic sequence under constant conditions.

Comparison between endocardial and epicardial roentgenological silhouettes allows us to follow ventricular volume and wall thickness changes under various conditions. For instance at the start of the experiment, we omit the contrast medium from the physiologic saline pumping liquid in the systemic circuit and follow ventricular volume changes as contrast medium is added to the pumped circulation.

During a typical 20 to 30 continuous angiographic analyses the stability of the ventricular function is demonstrated (Figure 5) by the reproducible beat-to-beat volume changes of the ventricle.
The constant pressures and stroke volume would suggest that beat-to-beat work and shape changes are also constant. However, some preliminary data indicates that the beat-to-beat volume and pressure changes over a period of time are not sufficient data alone to indicate ventricular functional status.

**Significance**

This preparation is ideally suited for analysis of the three-dimensional shape of the ventricle from its angiographic images. Perhaps the changes in left ventricular shape during this period of decreasing absolute ventricular volume may give us greater insight into the length/tension relationships of the ventricle.

To date five experiments with the preparation have been used to analyze ventricular function under these ideal angiographic conditions with various procedures. For instance:
a. High and low aortic pressure loads,
b. High and low left atrial pressure loads,
c. This preparation is particularly suitable for observing the effect of electrical stimulation of the ventricular myocardium in different places on the dynamic shape and function relationships in the left ventricle.
d. Infusion of drugs into the coronary circulation,
e. Occlusion of small coronary arteries.

All of these manipulations can be performed transiently or during steady state and this hopefully will increase insight into the regional myocardial function in total ventricular function. Measurement of regional myocardial function will require regional shape measurement which can be achieved by the three-dimensional shape reconstruction techniques.

Computer Controlled Video Digitization and Video Graphics

Aim

Digitization, communication, and display equipment and the development of algorithms and computer programs to manipulate and analyze the high volumes of data generated by roentgen video angiographic and ultrasound systems has been, and will be necessary in our attempts to fully exploit the potentials of multiplane video roentgenographic techniques. The amount of pictorial and hemodynamic data generated by the various research projects in this laboratory has reached astonishing proportions, and although a great deal of information is being gained by both conventional and sophisticated analyses of these data, additional objective and time economical measurements, determinations, and estimates concerning these data will be greatly facilitated and amplified by the application of high-fidelity quantitation and digital processing techniques. The installation of high-fidelity quantitation and digital processing techniques: the installation, interfacing and programming of the Biomation Model 8100 Transient Recorder (BTR) and Princeton Electronic Products Video/Graphic Storage Terminal (PEP) has added an entire new dimension to data acquisition and evaluation in that they will provide means for examining signal information and content which heretofore have not been attainable. The possibilities for gaining new insight into cardiovascular and cardiopulmonary performance by the application of computerized image enhancement, subtraction and feature extraction algorithms to high-quality digital representations of cardiac and lung roentgen video-grams are now at hand.

Method

The Biomation Model 8100 Transient Recorder (BTR) is a compact, solid-state electronic instrument which stores the digital equivalent of electrical waveforms in a memory. The BTR utilizes a very high-speed, 8-bit analog-to-digital converter with an aperture time (or sampling window) of less than 2 nanoseconds, and a maximum word conversion rate of 100 mHz (100 million
words per second or 800 million-bits per second) which is combined with a 2,048 word shift register memory. A digital-to-analog converter is also included to provide an analog output in addition to the digital output. The digital output is available at a maximum rate of 2 MHz (i.e., the entire memory can be read out in 1 msec). Versatile arming, triggering, and signal manipulations provide a variety of combinations for accomplishing the signal recording desired. The sample frequency can be selected in 1-2-5 sequence with time base of μsec, msec, or seconds to provide recording periods of 20 μsec (for 0.01 μsec interval) to 5 1/2 hours (one sample per 10 seconds).

The device might be best characterized as a digital oscilloscope, replacing the conventional CRT storage tube with a digital memory. Both external and internal timing and control are available. That is to say, that the unit can be operated independently or serve as a master or slave to other elements in a data acquisition system. An important capability featured by the BTR is that it can be readily interfaced to a digital computer for complete remote control of all the modes of operation that the BTR exhibits.

The BTR has been uniquely implemented into our video-computer system in association with several other devices: 1) a conventional scan converter for displaying computer-generated alphanumeric and graphic information; 2) a gray level storage scan converter for displaying computer-generated pictorial data (to be described in more detail later), 3) a light pen for x,y graphic input to the computer, 4) a 64-character keyboard for alphanumeric input to the computer, and 5) a television monitor for displaying both video and computer-generated information. The elements of this system are appropriately linked by a special purpose BTR/video/computer interface which monitors and conditions all communication between the system components. An important service performed by the interface is to provide synchronization and control of video signal recording by the BTR.

Several computer programs have been written and tested for using the BTR to digitize, store and display video pictures. These include 1) a calibration program to provide the proper mapping and relationship of units in the BTR, video and computer system, 2) an interactive program to allow the operator using the light pen to outline any irregularly shaped area in the video picture as presented on the television monitor and to have digitized according to selected parameters (e.g., amplitude and spatial resolution) only that portion of the video signal bounded by the specified area, 3) a program to store and retrieve files of digitized video data onto and from magnetic tape and disc, and 4) a program to facilitate the display of the digitized video pictures in various forms (e.g., single line density profiles, full gray level presentation, gray level contouring, and/or gray level slicing). It is worthwhile to note that the digitization program can digitize and store an entire video field of 500 lines with 2,000 points on each line at 256 gray levels (1,000,000 8-bit picture elements) in 15 seconds. Smaller areas of the video picture can be digitized in less time and, if preferred, with less amplitude and/or spatial resolution (e.g., 250 lines at 1000 points per line takes 7 seconds).

The next phase in the evolution of the BTR/video/computer system will be the continued development of general purpose user software to provide high-fidelity
signal quantitation and processing for a variety of research applications. The program described for selectively masking the quantitation of video signals will be immediately useful for applying video scanning densitometry techniques for measurement of left ventricular volume, regional circulatory perfusion of the kidneys, and regional pulmonary ventilation - all projects now or soon to be underway in our laboratory. This program could also be used to designate specific areas of chest x-rays for special digital processing, including regional subtraction and/or feature extraction, to facilitate the detection and delineation of regional abnormalities within the lungs. Other applications include the investigation of image-processing algorithms to more accurately delineate the outlines of intact cardiovascular structures and to obtain multiplane density profiles across these structures to facilitate the determination of their true shape and size in order to gain greater understanding of the mechanics of cardiovascular behavior. In addition, the system will be used to outline and selectively digitize individual human chromosomes from video recordings of optically magnified slides of stained chromosome preparations in an attempt to quantify and characterize chromosomal banding structure and to automate their homologous classification. The digitization of roentgen videographic exposures of canine lungs, tagged with uniformly distributed radiopaque beads, and subsequent computer tracking of the movement of these beads as a function of time and in compliance to various controlled respiratory positions and maneuvers in an attempt to quantitate regional pulmonary ventilation and lung volume changes, will soon be possible using the BTR/video/computer system. Application in quantitating and analyzing ultrasound data will also make extensive use of this system.

The Princeton Electronic Products - 400 Video/Graphic Storage Terminal (PEP) is an electrical-input/electrical-output scan converter capable of both high resolution graphics and full gray scale video image storage. It offers a number of significant advantages in performance and cost over other storage tube devices due to its multiplicity of uses and to the technological improvements in image storage made possible by the Lithicon™ storage tube. This tube features high writing speed, fast selective erase, and extended (non-destructive) readout of up to 1200 television lines with full gray scale. The advantages include the capabilities for video frame integration, storage of slow-scan X-Y generated images and video scan conversion with either internal or external synchronization. In addition, the ability to remotely operate the PEP unit via a logic control connector facilitates its use as an on-line peripheral computer device.

A special purpose controller has been designed to interface the PEP unit with the computer. The controller monitors and processes all communication between the computer and the PEP terminal to ensure operational fidelity, to provide functional status checks and to prevent tube damage. The controller also provides manual control of certain operational capabilities of the PEP unit, namely video frame recording and full screen erase. The controller communicates with the computer via the high-speed analog-to-digital and digital-to-analog converters and with the operator via a panel of labeled push buttons, switches and lights.

A set of computer programs have been written to facilitate the use of the PEP unit as a computer controllable device. The computer programs can be divided
into two general classes: 1) PEP system drive routines and 2) PEP system user routines. The first set of routines are the basic drivers of the PEP unit, providing the necessary and appropriate channel and line selections in the PEP-computer interface and supplying the proper magnitude, polarity, and frequency of signals to the interface for effecting all modes of operation of the PEP unit. The second set of programs are higher level routines which the user of the PEP system employs to avail himself of the services provided by the PEP system. These routines in turn call on the basic drive routines to accomplish their specific purpose. Included in the set of user routines is a program to test and evaluate the operation and function of the PEP unit. This program is specifically useful for "trouble-shooting" the PEP device and for estimating the fidelity with which it can be expected to perform. The rest of this section will briefly describe other general purpose routines provided for users of the PEP system.

**INITP**

This routine initializes the PEP system logic. All graphic controls are disabled and the unit is put in the video mode for display of information recorded on the PEP storage tube.

**VIDEOP**

This routine provides transfer of single frames of information from a video source to the PEP storage tube. The video input to the PEP may contain alphanumeric and/or graphic data from the Tektronix scan converter station or full gray scale video from the video disc. No erase is generated by VIDEOP and, therefore, the frames of video information snatched from the video source are superimposed on or integrated with the data currently recorded on the PEP storage tube.

**ITENP**

This routine provides intensity modulation of the PEP. The allowable intensity range is 0 to 32. The intensity value specifies the amount of erasure or the brightness of writing. The actual erase/write intensity is dependent on point-to-point spacing as well as the intensity value setting and therefore, some manipulation of point density versus intensity range may be necessary to achieve the desired gray scale for a given picture.

**ERASEP**

This routine provides selective graphic erase of the PEP. Each point is erased to a degree specified by the current intensity. The full screen can also be erased.

**WRITEP**

This routine provides selective graphic writing on the PEP. The point grid is 0 to 1023 in both Y and X. Each point is written at the current specified intensity.
LINEP

This routine provides generation of collinear points between two specified coordinates by digital differential interpolation. LINEP is provided as an efficient routine for generation of solid or dotted lines to facilitate the use of the PEP system for graphics.

These routines supply the user of the PEP system with the basic programming tools necessary to communicate with the PEP unit. They were written for maximum efficiency with respect to storage and execution time requirements as well as general applicability.

The figures on the following pages illustrate the use of the BTR and PEP systems for digitizing video pictures and for displaying the digitized information in various graphical formats. The picture presented is a single television frame of a human biplane left ventricular angiocardiogram as recorded onto a video disc recorder and replayed in stop-action. The subsequent digitization and reconstruction of a selected portion of this picture is detailed in the figure captions.
These routines supply the user of the PEP system with the basic programming tools necessary to communicate with the PEP unit. They were written for maximum efficiency with respect to storage and execution time requirements as well as general applicability.

The figures on the following pages illustrate the use of the BTR and PEP systems for digitizing video pictures and for displaying the digitized information in various graphical formats. The picture presented is a single television frame of a human biplane left ventricular angiocardiogram as recorded onto a video disc recorder and replayed in stop-action. The subsequent digitization and reconstruction of a selected portion of this picture is detailed in the figure captions.

Figure 6  Biplane angiocardiogram of a human left ventricle as displayed in stop-action from the video disc recorder. The picture is displayed on the television monitor at the BTR/video/computer terminal and represents a point in the diastolic phase of the cardiac cycle. The two silhouettes are orthogonal projections of the left ventricular chamber as recorded by a biplane roentgen-video system following injection of contrast media into the left ventricle. Both images are recorded in the same video frame using a split-screen television technique.
Figure 7  Example of a rectangular window for selective digitization of the video information within the window. This type of video digitization mask is generated by positioning the cursor with the light pen at the upper-left and lower-right vertices of the desired rectangle. Once such a digitization mask is specified only the television lines within the rectangle will be digitized. The desired spatial and amplitude resolution of the digitization is specified before digitization begins.
Figure 8  Example of an irregularly shaped window for selective digitization of the video picture. The window is specified by tracing the desired boundary on the picture with the light pen. As in the case of the rectangular window, subsequent digitization of the video frame will be restricted to that portion of the picture bounded by the specified outline. The message at the top of the picture indicates that the top horizontal video line of the window is 92 and the last video line intersected by the window is 197. There are a total of 250 horizontal video lines in the picture. The maximum diameter in the window contains 372 sampled points (1079-708+1=372). The message also indicates that the maximum intensity level within the window is 247, the minimum intensity level is 79 and the average intensity level for the entire window is 123.
Figure 9  This picture illustrates the display of a single line intensity profile following digitization of the video information within the specified window. Every video line within the mask was digitized at a frequency of 20 mHz (.05 usec between samples) yielding approximately 372 points across the maximum diameter of the window. (At this frequency 1270 points would be digitized on a full horizontal line). The profile selected for display was line 155. This line is depicted by the brightened horizontal line across the picture. The picture intensity profile intercepted by the window on this line is plotted below the window in approximate spatial relationship to the window diameter on line 155. The maximum intensity level in this profile is 242 and the minimum intensity level is 85 in a possible range of 0 to 255, as depicted by the scale at the left of the picture.
Figure 10 Graphic, gray level reconstruction by computer on the PEP storage terminal of the digitized window illustrated in Figures 8 and 9. Only every third point on each digitized line within the window is plotted to maintain an approximate aspect ratio relative to the original picture. 32 gray levels are used in the generation of this display. The moire pattern which can be observed is due to display noise and is not present in the digitized representation of the pictures.
Figure 11  Reconstruction by computer on the PEP storage terminal of the digitized window illustrated in Figures 8 and 9. The display resolution is the same as in Figure 10 except only 4 gray levels are plotted. That is, the entire gray level range of the digitized picture is portioned into 4 levels over the same range. This type of gray level contouring can be helpful in studying regional density distribution and gradients.
Figure 12 Computer-generated display on PEP storage terminal of the digitized video window in Figure 7. The display is the same as in Figure 10 (32 gray levels) except that the specific gray level 13 is represented by an intense level wherever it occurs in the picture. This technique of "level slicing" often results in contoured outlines which facilitate the recognition of object boundaries when the perimeter of the object maintains a relatively constant gray level.
Parenchymal Distortion: Techniques of Tagging the Lung Parenchyma and Measurement and Analysis of Its Regional Displacement as a Measure of Regional Ventilation

Method

A technique of roentgenographically tracking the pulmonary parenchyma has recently been developed utilizing 1-mm diameter of metallic markers distributed throughout the pulmonary parenchyma (Greenleaf et al., Physiologist 14:155, 1971; Smith et al. Physiologist 14:232, 1971). By roentgenographically tracking the spatial positions of 30 to 40 1-mm diameter metallic markers, regional displacement of pulmonary parenchyma can be quantitatively measured. This technique can be used for dynamic studies of the spatial distributions of ventilation, pressures and stress-strain relationships through the lungs under conditions of gravitational and inertial conditions.

The distance between any two markers within the lung can be considered to be a measure of the distention of that region. Changes in regional volume should be proportional to the cube of the change in distance between two adjacent markers. Regional distributions of changes in pulmonary parenchymal volume can be determined from the regional distribution of relative changes in distance between adjacent marker pairs distributed throughout the lung. Changes in these regional volumes are proportional to regional ventilation. Comparison of ventilations measured with the use of the markers can be made with distributions of ventilation utilizing two additional but independent methods.

1. Radioactive Aerosol

By tagging the first 50% of the volume of a breath with a dense cloud of radioactive aerosol (Gold 198), regional ventilation for that breath can be measured from the regional distribution of radioisotopic activity. This distribution of activity can be measured by externally scintiscanning the thorax with a specially modified computer-controlled scintiscanner designed and built in this laboratory. Programs have been written which control the scanner, remove collimator distortion and calculate and display three-dimensional contour maps of the radioactive distribution over the thorax of the animal.

In this case the radioactivity will be proportional to the distribution of ventilation within the thorax.

2. Roentgenological

Transirradiating the thoracic cavity with x-ray energy and recording the projected roentgen silhouette on videotape provides a dynamic record of regional pulmonary roentgenographic density as a function of time. This roentgenographic density is dependent on the quantity of air traversed by the transirradiating beam. Since these animals are immersed in a water-immersion fluid plethysmograph respirator (Sass et al., J Appl Physiol 32: 451, 1972), the quantity of water traversed by the x-ray beam varies with ventilation.
3. Radiopaque Pulmonary Parenchymal Marker

The development of programs which will automatically track the distribution of metallic markers as recorded on biplane videoangiograms will greatly facilitate the study of dynamic regional distribution of ventilation. These programs make it possible to measure the distribution of pulmonary displacement and volume change every 1/60th of a second. This will allow measurements to be made at higher resolution both temporally and spatially than previously achieved.

Significance

The three techniques described above will provide three independent measures of the regional distribution of ventilation. Each technique measures a different form of ventilation. Metallic markers measure total change in volume due to changes in ventilation, dead space, and blood volumes. Aerosols measure only the air delivered to the alveoli. Roentgenographic density measures collateral ventilation along with true ventilation. Correlations of the three measures should provide additional understanding of the regional distribution of ventilation and factors which affect it.
PUBLICATIONS


20. Sass, D. J., A. C. Nolan, and E. H. Wood:
Digital computer analysis of circulatory and respiratory pressures in
water-immersed dogs breathing liquid in force environments of 1 and 7Gy.
Aerospace Medicine (submitted).

The spatial distribution of pulmonary blood flow in dogs in the left
decubitus position.

22. Avasthey, P., and E. H. Wood:
Intrathoracic and venous pressure relationships during responses to
change in position.
Circulation (submitted).

23. Ritman, E. L., R. E. Sturm, and E. H. Wood:
Sixteen-channel, thousand-samples per second, analog signal recording
on videotape suitable for analog-to-digital conversion.

Digital computer analysis of circulatory and respiratory pressures in
water-immersed dogs breathing liquid in force environments of 1 and 7Gy.
Aerospace Medicine (submitted).

Effect of duration of +Gy acceleration on spatial distribution of
pulmonary blood flow in dogs. (in preparation).

Effect of changes in magnitude of force environment on regional pulmonary
displacement and volume of dogs in left lateral position. (in preparation).

27. Sass, D. J., J. F. Greenleaf, and E. H. Wood:
Effects of +Gy acceleration on the regional distribution of pulmonary
blood flow in dogs breathing organic liquids in a whole-body water-
immersion respirator (in preparation).

Gas embolism in dogs due to intravenous FC 80 liquid fluorocarbon.
(in preparation).

D. J. Sass:
Effect of magnitude, direction and duration of gravitational-inertial
force on pulmonary blood flow in chimpanzees (in preparation).

R. E. Sturm, and E. H. Wood:
A biplane roentgen videometry system for dynamic studies of the shape
and size of the human left ventricle (in preparation).
31. Sturm, R. E., and E. H. Wood:
The Bessel Filter (in preparation).