Light-Pen Computer Processing of Video Image for the Determination of Left Ventricular Volume

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SUMMARY
A volume angiography system for on-line computation of left ventricular angiograms has been developed utilizing a video disc recorder, a light-pen unit, and a digital computer. The video disc recorder allows for immediate replay and stop-motion of ventricular angiograms on a video monitor. The light-pen is used by a technician/physician operator to define the margins of the ventricular chamber and input the data directly to the digital computer. The computer, utilizing the area-length method, applies preset magnification factors and calculates the ventricular volume. Comparison of this light-pen computer system with conventional manual processing of cine film yielded a correlation coefficient of 0.99. The equipment configuration employed in this system offers the advantages of available hardware components and operational simplicity. The major benefit has been avoidance of the logistic delays involved in cine film processing and handling, which have been obviated by the on-line capability of the video disc, light-pen, and computer combination.

Additional Indexing Words:
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The usual method for determination of ventricular volume from left ventricular angiograms involves a series of three steps. The first step is recording the angiogram, the second is defining the margin of the left ventricular chamber, and the third is area integration and use of appropriate formulae for computation of volume. Conventional methods for determining volumes have in the past involved time-consuming and tedious technics of recording on film, drawing the margins on paper, and integrating the areas by hand. Utilizing developments in electronics over the past decade, advances have been made in each of these three areas. The availability of video disc recorders has made it possible to locate and replay individual angiographic frames almost immediately following recording. Margin definition has been speeded by the introduction of cine film projectors, coupled with manual X-Y plotting devices.

Computers have been used, not only to process the information generated by the X-Y plotter, but also to perform border recognition automatically. This latter technic necessitates operator interaction for initiation and/or verification of the computer-defined margins. The video image processing systems, thus far reported, which utilize video disc recording and computer processing of the video image, have emphasized frame-by-frame analysis of individual cardiac cycles at the price of substantial equipment complexity and cost.

A light-pen computer system has been developed in our laboratories at Stanford Medical School to facilitate margin definition by the operator, and simultaneously to transfer data into a small digital computer. Calculation of ventricular volumes is then performed, using the area-length method. The goals of this system were to provide the catheterization laboratory with an on-line method for determining left ventricular volumes at reasonable cost, utilizing readily available video components.

System Design

Components
A block diagram of the present integrated system for ventricular volume determination is shown in Figure 1. Left ventriculograms are obtained with the heart in a 40° right anterior oblique projection, using a 50-cc...
injection of Renografin-70 (meglumine diatrizoate) over a 3–4-sec interval. The ventriculogram is recorded on a Data Memory Inc. video disc, using a plumbicon television camera. Recordings may be performed with the radiographic equipment either in the cine or fluoroscopic mode. The video disc is capable of recording X-ray pictures at a rate of 15 frames/sec, with a storage capacity of 400 frames. The disc recorder plays back the angiogram on a video monitor, both forward and backward, at rates of 3.75, 7.5, and 15 frames/sec, and has single-frame viewing capability. An electronic counter is provided for identification of each individual recorded frame. In order to identify end-diastolic frames of the angiogram, a radiopaque mechanical event marker (Electronics for Medicine), which is triggered by the R wave of the electrocardiogram, is positioned within the radiographic field at the time of the angiogram.

A light-pen unit (Tektronix 4551) is used to "draw out" the margins of the left ventricle as it appears on a video monitor. The pen itself is a flexible hand-held fiberoptic bundle, which conducts the light from a specific point on the video monitor to a photomultiplier tube. The video light pulses received by the light-pen, when correlated with the horizontal and vertical video sweep information, identify the precise aim of the fiberoptic bundle. This position is indicated on the video monitor by a bright cross. A pressure-sensitive switch on the light-pen allows the operator to instruct the cardiac catheterization laboratory computer system to sample the X-Y coordinates of the light-pen position.

This computer, Hewlett-Packard 2115A, is a small, on-line digital computer, with 8K of core, capable of executing any of a large number of programs stored on a digital magnetic disc. This computer has previously been programmed for pressure and output computations involved in cardiac catheterization. Computer programs are initiated and directed from a small keyboard located in the catheterization laboratory. Alpha-numeric computer output, utilizing a scan converter unit (Tektronix 4501) is distributed and displayed to laboratory video monitors, the video disc, and a video distribution amplifier (TeleMation Model TMV-551). Utilizing the subtraction-composite feature of the video disc, the scan converter image is subtracted from the recorded ventricular angiogram, and the superimposed images are displayed on a standard video monitor (Tektronix 630). Synchronization of the scan converter, light-pen, and video disc is performed by a broadcast synchronizing generator (TeleMation Model TSG-200).

Operation

Under the direction of the keyboard in the catheterization laboratory, the program for computing ventricular volumes is called from the magnetic disc into the computer. The computer displays on the video monitor four alternative instructions: "SYS" (systole), "DIAS" (diastole), "STOP," and "ENTER," in each of four quadrants (figure 2, bottom). By pointing the light-pen to one of the four quadrants where the instructions are displayed, and by touching the
pressure-sensitive switch, the computer executes that specific instruction. "SYS" or "DIAS" tells the computer whether an end-systolic or end-diastolic volume will be drawn next, and also labels the numbers which display the value of these volumes. The "ENTER" instruction cumulatively averages the most recent volume measurement into the appropriate register, and the "STOP" instruction terminates the program. The operator of this system, by viewing the replayed angiogram on the video monitor, initially selects an individual frame from the video disc for volume analysis. Using the light-pen, an outline of the ventricular chamber is traced, starting with the edge of the aortic valve which is farthest from the apex. This initial starting point identifies one end of the ventricular long axis needed for the ellipsoid model computation.8 When the pressure-sensitive switch is pressed, the X-Y coordinates of the cross, as seen on the video monitor, are fed to the computer, and the track of the light-pen as it moves around the ventricle is retained by the scan converter on the video screen (fig. 2). Immediately upon releasing the pressure-sensitive switch at the end of the tracing of the chamber outline, the computer applies the area-length method for determining volume. Calculated volume is corrected for image magnification by entering numeric data from the keyboard concerning left ventricular position. The corrected value for ventricular volume is then displayed on the bottom of the video screen (fig. 2). At this time, the operator has the option of entering that volume into a cumulative average. If not satisfied with the drawing of the image margins, he may instead erase the volume measurement and initiate another drawing by pointing the light-pen at 'SYS' or 'DIAS' again. Using a Tektronix C-5 camera, the outline of the ventricle and the computed volume may be readily photographed on Polaroid film (fig. 2). The entire procedure for determining ventricular volume on a preselected video frame requires no more than 2-3 min.

There is also a provision within the program for calibrating the light-pen system which allows compensation for X-ray image magnification. All angiograms are performed at a fixed tube-to-image intensifier distance.
Thus, there is a constant proportionality between magnification and height of the left ventricle above the X-ray tube. Left ventricular position is determined using either echocardiographic technics, or by assuming the left ventricular position to be half of the anterior posterior chest diameter. Magnification was determined by recording a 10 x 10 in., 1-cm crosshatched grid at 1-cm heights between the table top and image intensifier. The correction factor for magnification was measured by pointing the light-pen at the corners of the central 6 x 6-cm portion of the recorded grids which most closely approximated the area of the usual ventriculogram. A correction factor representing the ratio of true length of one side to the calculated length was then determined by the computer. The error introduced by spherical distortion in cases of very large or very small ventricles was less than 3%. Figure 3 illustrates a comparison of computer and cine determinations of area correction factors for different grid heights above table top. The overall relationship of area correction factor to object distance from the X-ray tube is quadratic; however, over the range of left ventricular positions encountered which represent 10% of the total tube-to-image intensifier distance, the relationship is nearly linear. The slopes, as illustrated in figure 3, were very similar within this range of left ventricular positions. The absolute differences in the area correction factors are due to the arbitrary units of the analog-to-digital converter which processes the X-Y coordinate data for the computer.

Validation Procedures and Results

Statistical Correction for Ellipsoid Model

Ten latex casts of postmortem ventricles of varying size and volume were positioned on the radiographic table, in such a way that the apex was tilted upward 20° and leftward 10°. The fluoroscopic image of the latex ventricular casts, in both the 40° right anterior oblique (RAO) and posterior-anterior (PA) positions was recorded on the video disc for light-pen computer determination of volume, and on cine film for manual determination of volume. Volume of the ventricular casts was determined by weight, with correction for the specific gravity of latex (1.050). Figure 4 illustrates

Figure 3

The magnification factors determined using the light-pen computer system and using conventional cine processing are plotted against the grid height above the table top. Image intensifier-to-tube distance was kept constant. The absolute value of the magnification factors are different because of the methods employed; however, the slopes are virtually identical.
a heart model of known volume, the display of the model on the video monitor, and a Polaroid picture of the scan converter screen showing an outline of the model as drawn by the light-pen, with the computer calculation of the volume of that chamber.

Figure 5 illustrates the regression lines generated by both the light-pen computer and cine-manual methods for determining ventricular volumes in the AP and RAO projections. Utilizing the light-pen computer system, the regression line for models in the AP position was: \( Y = 1.07X - 7.7 \), where \( Y \) = corrected volume and \( X \) = calculated volume. The light-pen computer regression line for models in the RAO projection was: \( Y = 0.92X - 3 \). The light-pen computer and cine-manual methods yielded very similar volume measurements.

Comparison of Light-Pen and Cine Methods for Ventricular Volumes

Utilizing the above regression lines for statistical correction of calculated volumes, routine left ventricular angiograms were analyzed by both conventional cine methods and the light-pen computer method. Eleven consecutive left ventriculograms in patients undergoing evaluation for valvular insufficiency were recorded in the 40° RAO position simultaneously on 35-mm cine film at 48 frames/sec and on the video disc at 15 frames/sec. Computation of end-diastolic and end-systolic ventricular volumes was performed by conventional manual planimetry of cine film images and by light-pen computer processing of the video image.

Figure 6 shows the results of comparison of end-diastolic volumes and end-systolic volumes in the same patients. The correlation coefficient for the
A comparison of the true measured volume of the latex models against the calculated volume of the models, using both the light-pen and cine methods, is shown for both the anterior-posterior projection (left) and for the right anterior oblique projection (right). The light-pen and cine data are quite similar, as are the regression lines.

Comparison of both end-systolic volumes and end-diastolic volumes was 0.99. The SD of the difference of the light-pen method from the cine method for determining end-systolic volume was 11.1% of the cine mean. For the determination of end-diastolic volume, the SD of the difference of the light-pen method from the cine method was 6.2% of the cine mean.

A comparison of the light-pen with cine method for determining left ventricular volumes is shown for both end-diastolic volumes and for end-systolic volumes. The correlation coefficient for end-diastolic volume was 0.995, and for end-diastolic volume was 0.991.

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Discussion

There are several important factors in the development and general application of a computer system for the analysis of ventricular angiography. These are image quality, ease of operation, minimal equipment complexity, avoidance of operational constraints, and cost. Each of these factors must be taken into account in analyzing the three major steps in video image processing: recording, margin definition, and computation.

Recording

The video disc recorder is currently the most expensive and technologically the newest component of this volume angiographic system. The particular disc recorder used with the studies reported in this paper, although recording at only 15 frames/sec, yielded comparable ventricular volumes to those measured from cine film at 48 frames/sec. More rapid recording speeds such as 30 frames/sec are clearly desirable to improve still further the accuracy of end-diastolic and end-systolic measurements, particularly at rapid heart rates. In addition, the faster recording rates would provide capability for frame-by-frame analysis of individual cardiac cycles. Such equipment is currently available and under evaluation (see Addendum). In addition, recording the left ventricular angiogram on the video disc with the radiographic equipment in the cine mode necessitates close synchronization. During normal cine operation, X-ray pulses are triggered by the cine camera. The cine camera frame rate is mechanically determined, generally operating with slight frequency instability, incompatible with video disc recording rates, which are tightly synchronized to multiples or submultiples of power-line frequency. This results in dark, horizontal bands traveling across the video monitor in the vertical direction.9 Synchronous recording with the radiographic equipment in the cine mode has been accomplished subsequent to collection of the data presented in this paper using a regulated power supply to drive the cine camera at precisely 60 frames/sec which is a multiple of the video disc recording rate.

In our experience, the video disc recorder is capable of reproducing angiographic frames of comparable quality and resolution to cine film. The capability for adjusting brightness and contrast on the video disc offers many advantages over cine film, where such results can be obtained only by special optical or printing processing of the resultant film. Tape-recorded angiograms do not offer the advantages of variable frame-rate viewing and have difficulty providing good quality stop-motion frames. They can, however, be utilized for storage of angiograms, which can be individually processed by rerecording the information on a video disc. By far the greatest advantage of video disc recording is its on-line capability to reproduce angiograms for ventricular volume computation.

Margin Definition

The definition of ventricular margins in this system is entirely dependent upon the experience and skill of the technician/physician operator. Although computer technics have been developed for automated margin definition, these technics are cost-prohibitive. Human supervision utilizing a light-pen, mask, or multiple electronic adjustments is still required to define limits for the automated border recognition programs, to compensate for variations in background density and to fill in gaps in undefined areas such as the mitral valve.3-5 The light-pen, which is currently available hardware and relatively inexpensive (approximately $1800), provides a rapid method of feeding data directly into the computer as it is being generated by the physician who is drawing out the chamber margins. A more complex light-pen computer system, with videodensitometric capability, has been developed by Heintzen et al.10 This system stores the light-pen generated ventricular contour on a scan converter by means of a specially designed sweep-stop unblank unit. A coding and counting unit then delivers the ventricular boundary data to a digital computer. Excellent correlation of light-pen computer volumes with test objects of known volume were observed using this latter system. The validation procedures we carried out confirmed that volumes computed using the light-pen computer system compare closely to those calculated using conventional cine-manual methods. The light-pen in our system is not only used for definition of ventricular contours, but also for feeding instructions into the computer.

Computation

The third aspect of measuring ventricular volumes is the computational phase. The calculations involved are relatively trivial and can be handled by very small digital computers. They involve the determination of area using Green's theorem and the maximal image-cord length as determined from the flag point initiating the drawing, as shown in figure 2. The programs are also sufficiently compact, such
that they can be stored either on a magnetic card or magnetic tape device, rather than on a more expensive digital data disc.

The major cost of the system described is the video disc recorder ($15,000–$24,000). Despite this obvious drawback, many laboratories have such a recorder because it provides for stable stop-motion instant replay, subtraction capability, and continuous update with replay of the last retained image. For those laboratories which have a video disc recorder and access to a small computer, the added cost of the light-pen, scan converter, and synchronization electronics is approximately $5000.

The main advantage of this light-pen computer system is that logistic delays involved in cine-film handling are obviated. The physician performing the catheterization can immediately, upon completion of the angiogram, draw out the ventricular volume as needed. This allows accurate measurement of valvular regurgitation, and ventricular contractility during catheterization procedures. Equipment complexity has been kept to a minimum, and there are very few constraints upon the operator of such a system. At present, modifications are under way to increase the frame rate and improve disc electronics to provide interface capabilities with various X-ray systems.

Addendum

Since the submission of this manuscript, routine determination of ventricular volumes using the light-pen computer system has been carried out in 80 patients. An Ampex DR-10A video disc recorder with 30-frames/sec record speed and 600 frames of storage has been employed for more recent studies. Specific video disc modifications have permitted simultaneous recording of the electrocardiogram and left ventricular pressure as individual horizontal bars on each video frame. These improvements have resulted in more precise measurement of end-diastolic and end-systolic volumes and provide capability for frame-by-frame analysis of simultaneous pressure and volume data.

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