The television/computer system—The acquisition and processing of cardiac catheterization data using a small computer*

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INTRODUCTION

One of the prime objectives of cardiovascular research is to assess the functional state of the heart especially the left ventricle, its main pumping chamber. The functional state of the left ventricle is determined by its dimensions, volume, the velocity of wall movement, the intracavity pressure, and the wall tension and stress.

This paper describes a semi-automated technique for obtaining parameters which indicate the functional state of the heart from left ventricular cineangiograms (35 mm. X-ray cine films of the heart taken while injecting a contrast material into the pumping chamber) and simultaneously recorded intracardiac pressures. Doing the measurements necessary to obtain function data is tedious and time consuming as dimensions must be measured from each frame of a cineangiogram of the left ventricle taken at 60 frames per second over several seconds, and correlated with the instantaneous cavity pressure. Displaying resultant function parameters in an intelligent fashion is also critical if they are to be useful to the clinician.

Two years ago the Cardiovascular Laboratory at Toronto General Hospital undertook to quantitatively assess the functional state of the human left ventricle. The resources available to this department dictated that any application of data processing equipment be modest, and that the equipment be housed within existing space. We, therefore, chose a small computer, optimizing on both the low cost and expandibility of a local on-line system and the availability of software, peripherals and interfacing electronics. This equipment in conjunction with a standard broadcast television system provides a powerful data acquisition and processing facility which occupies one office in the unit and has the capacity to deal with the large volume of multi-formatted data (digital, analog, pictorial, patient records) resultant from heart investigation procedures.

The total cost of the system has been about $100,000 for hardware and $20,000 for personnel. It is being used for research and development and is more sophisticated than necessary for routine work. For routine work a simpler configuration can be used. For example, a minimum system might include: a PDP-8/E ($5,000), a teletype ($1,700), disc or tape ($8,000–$10,000) interfacing ($2,000–$4,000), and some basic television equipment ($5,000), or not more than $27,000.

Other techniques have been developed for obtaining this information. They range from totally automated border recognition and dimension extraction systems to hand measurements. Between these extremes, there are: (a) semi-automated systems similar to ours, the Bugwatcher, which uses a much more expensive computer, is very similar to ours in design, but is not used for cardiovascular work, and (b) a light pen system which obtains border coordinates by standard X-Y position digitizers or scanners.

Totally automated systems involve long setup procedures, the digitization of entire pictures, and the presentation of this data to a large computer for analysis. This is often slow and extremely expensive. On the other hand, manual measurements are tedious, time consuming and the resultant data often requires some machine processing.

Three systems similar to ours have been developed. Two use a dimension measuring interface similar to the one described in the text and illustrated in Figures 3–7: (1) the Bugwatcher, which uses a much more expensive computer, is very similar to ours in design, but is not used for cardiovascular work, and (2) an analog

* Work supported by the Ontario Heart Foundation and Toronto General Hospital

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system, which, although real-time operation appears possible, suffers the limitation of having to depend on an expensive video magnetic disc and of making only area, length and one left ventricular width available as data. The third uses a light pen similar to that described here, but employs a scan converter and storage oscilloscope instead of a magnetic disc recorder for refreshing the display, and is less flexible in use.

THE TELEVISION/COMPUTER SYSTEM

The system we have designed (Figure 1) is based upon interfacing a television system with a small computer. The television system (Table I) (standard 525 line broadcast equipment), is inexpensive but very flexible. We use television as a brightness/voltage, dimension/time converter for pictures. In addition, available television circuits permit a number of useful functions, e.g., selecting parts of a picture for examination, changing the quality of a picture, superimposing windows or other signals on a picture, recording televised signals, and presenting calculated or plotted data.

The main features of this work are the interfaces which permit the analog signals from the television system to be converted into digital format for input to the computer and allowing the computer, in turn, to communicate with the television system. The interfaces

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**Figure 1**—Diagram of the Television/Computer System. The computer (DEC PDP-8/I) can transfer data to or receive it from a number of peripherals (see Table II, text). The television system is composed of a master synchronization generator and sync and video-distribution circuits (see Table I, text for details). In addition, there are the interfaces which connect the computer and television systems. These include: the dimensional analysis interface (DAI), the light pen and light pen interface (LPI) and the analog-digital (A/D and D/A) converters. Certain peripherals are shared by both systems, permitting easy communication between them.

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**TABLE I—The T.V. System**

The main sub-elements of the Television System are:

1. Monitors (CONRAC, SONY, H/P)
2. Number and bar generating circuits
3. Television cameras (SHIBADEN)
4. Magnetic Tape (SONY 2")
5. The Vista 1 H
6. The Video Disc
TABLE II—The Computer System

The computer peripherals available to the 4K PDP-S/1 are:

1. Magnetic tape (DEC, TU-55)
2. 32K Magnetic Disc (DEC, DF-32)
3. A/D, D/A converters, relay drivers, pulse inputs (DEC, AXOS)
4. Oscilloscope display (TEKTRONIX, RM 503)
5. Teletype (ASR-33)
6. 180 LPM printer and graphic output terminal (LEIGH, ALPHAGRAPHIC)
7. 4800 Baud CRT terminal (INFOTON, VISTA 1 H)
8. Video disc via the AXOS (COLORADO VIDEO, VIDEO PLOTTER)

ensure that the dimension data measured from each television line in a picture are identified with that line, and are presented to the computer at an acceptable rate.

The computer, a 4K PDP-S/1 (recently upgraded to 8K) has available to it a number of standard peripherals (Table II) for inputting and outputting the data and for combining dimension data with other measurements during catheterization.

Presently, these measurements are made after the films obtained during cardiac catheterization are processed and returned to the unit. This entails a delay of about 24 hours before the catheterization data is available. However, ultimately our aim is to obtain data directly from video tape recordings of the angiogram and to play back the results into the television system during the catheterization.\(^{22,23}\)

CARDIAC CATHETERIZATION

Cardiac catheterization is done by introducing catheters (small, 2 mm. O.D., tubes) into the peripheral arteries or veins and advancing these into the heart chambers. The catheters are used to record pressure or to inject radio-opaque material to obtain high-contrast serial X-ray pictures of the chambers of the heart. In left ventricular function studies, one catheter is used for injecting contrast material and one for monitoring pressure. The main data obtained from this procedure are: (a) sequential films of the left ventricle (left ventricular cineangiograms) and (b) the analog left ventricular pressure recording.

In our work the angiograms have been recorded on 35 mm. cine film at 60 frames per second directly from an image intensifier (Figure 2). However, it is also possible to process full-size films from a high-speed film...
Figure 4—Schematic diagram showing how measurements are obtained from a television picture. When a line of the T.V. scan crosses the left edge of a dark image, a fall in the video voltage below a Schmitt trigger threshold starts a 10MHz clock, when the line crosses the right edge of the image the rise in the video voltage stops the clock. The number of clock pulses is proportional to the width of the image and the number of television lines crossing the image is proportional to its length. The threshold can be adjusted to define the edge of the image and a special effects window allows manual selection of the area of the picture which contains the image to be measured.

LEFT VENTRICULAR FUNCTION DATA

Dimension data

The Dimensional Analysis Interface (DAI)

Dimensions are measured from 35 mm. cine film projected onto paper by a stop frame projector (Tage Arno). A technician outlines the ventricle in each frame, draws axes on the outlines, cuts them out and puts them one-by-one on a light box where they are viewed by a television camera. Alternatively, dimensions may be measured directly from each 35 mm. cine frame (Figure 6). The results obtained directly from film are less consistent than those obtained from cutouts. However, with model studies, the differences between measurements from film and cutouts were not significant.

The television image is input to the Dimensional Analysis Interface (DAI). The dimensional analysis interface measures the width of the image on each television line by a threshold technique and (Figure 4) makes the width and corresponding line number available to the computer. The way this is done is shown in detail in Figures 3–6. Programs calibrate the measured widths and length (proportional to the number of television lines crossing the left ventricular image) and calculate scaled widths, the area, the length and volume. The latter is calculated assuming that the left ventricle is circular in latitudinal cross-section. The raw data is output on paper or magnetic tape (Figure 7). The tape record is later processed by programs which compute wall tension, stress, velocity and plot any selected dimension data.

Figure 5—Schematic diagram of the DAI. Voltage transitions in the video signal turn on or off a Schmitt trigger which has an adjustable threshold. The output of the trigger is gated with the signals from the computer, with the television FIELD drive and BLANKING signals, and with the switching waveform from a SPECIAL EFFECTS generator. When these input conditions are satisfied, the time the trigger is on for each television line is measured by the number of clock pulses accumulated in a “width” register and is fed back to the television monitor as a bright line (Figure 6). The line number is recorded in a second register. At the end of each line during which the clock was on, the output control transfers the width and line registers to their respective buffers and indicates to the computer that it is ready for a TRANSFER REQUEST. When a TRANSFER REQUEST is received by the output control, the contents of the buffers are copied into the computer accumulator through a series of output gates and level converters.
Figure 6—Cutout (top) and film (bottom) television images (left) along with a representative video waveform (center) and the feedback images from the DAI (right). The “window” surrounds both the television and feedback images. The video waveform is from the brightened line that crosses the upper part of the images. The video waveform of the cutouts has sharp edges, high contrast and is uniform, whereas that of the film has a diffuse edge, lower contrast and is not uniform. The result is that the measurement of the cutout is much more accurate and objective than that of film and that small changes in the threshold of the trigger will alter the measured size of the film image but will have little effect on the measured size of the cutout.

The light pen and light pen interface (LPI)

Because obtaining cutouts for use by the dimensional analysis interface is tedious and time consuming, the light pen and light pen interface were developed to input the left ventricular border directly to the computer and to further reduce the time involved in processing dimension data. With the light pen, the image of the left ventricle displayed on a television monitor from 35 mm. film or video tape, is outlined manually, the coordinates of the border being input by the interface directly to the computer. This system is illustrated in detail in Figures 8-10. Two monitors are used in practice, one to allow viewing of the picture with adequate contrast, the other for use as a “tablet”. All the operator needs to do is advance the film frame he wishes to process, outline the border as he recognizes it by eye, and indicate to the computer that the border is complete. The video disc constantly refreshes the track of the light pen and keys this into the picture the operator is viewing. The computer is interrupted 60 times per second to accept the X and Y coordinate of the position of the light pen. Multiple terminals are thus easily accommodated even by a small computer.

Analog signals: pressure

The trace marker

When first using the dimensional analysis interface (DAI) to process cutouts, pressures were obtained from
Figure 7—These are flow charts of two programs: VOLZ which calculates the dimensions of images and WVOL which calculates the calibration factors. The latter can be run in a repetitive mode to check the operation of the system and detect electronic faults. Because of the high data rates, both VOLZ and WVOL simply store the measured widths and their corresponding line numbers in assigned memory areas until the buffers are full. Thus, several scans of the same image are available. Checks are done to ensure that no lines were missed and that each discrete image is chosen from the several scans stored in memory. This is done by checking for sequential line numbers.

the oscillographic tracings on which the time of occurrence of each cine frame was marked (Figure 11). A line was drawn by hand from each mark to the left ventricular pressure tracing and the pressures read off, calibrated and tabulated by hand. This method of obtaining instantaneous pressures was used on 80 cases in conjunction with the DAI and cutouts. It is tedious and involves many possible inaccuracies. In particular, there is the possibility of losing the time correlation between the cine frames and the pressure tracing.

To ensure correlation between the film frames and the instantaneous left ventricular pressure it is necessary to guarantee that neither the oscillographic paper nor the film has stopped. Also, frames and trace marker pulses must be counted accurately until the heart cycle of interest is reached. To assure us of the

Figure 8—The track of the light pen placed against a monitor displaying a blank, bright raster (monitor #1) can be recorded by the video disc. This track may be keyed (SEG KEY) into the output of a television camera which is viewing a cine film (monitor #2), permitting an operator to outline areas of interest in the picture viewed by the television camera. Simultaneously, the digital horizontal and vertical coordinates of the position of the light pen can be output to the computer by the light pen interface.

Figure 9—Schematic diagram of the light pen interface (LPI). The FIELD drive pulse clears the HCR (Horizontal Coordinate Register) and the VCR (Vertical Coordinate Register) and provides input conditions to the CLOCK GATE and the INHIBIT. During a television line the BLANKING signal provides a condition to the INHIBIT. At the beginning of each line the BLANKING adds a count to the VCR if the VCR GATE is not inhibited and starts the clock if the CLOCK GATE is not inhibited. The output of the clock is recorded in the HCR. If a light pen pulse (LPP) does not occur before the end of a line, the BLANKING clears the HCR through the LINE CLEAR GATE. If an LPP occurs during a line, a Schmitt trigger (ST) turns the INHIBIT on. The latter INHIBITS the VCR gate, the LINE CLEAR GATE and the CLOCK GATE effectively freezing the contents of the HCR and VCR. The INHIBIT also provides a signal to the output control indicating to the computer that the contents of the HCR and VCR are available for transfer.
simultaneity of the two records, a second trace marker was added which has every tenth mark accentuated and which uses this accentuated mark to place a bright dot on every tenth film frame. In this way the number of errors due either to stopped recordings or counting mistakes has been greatly reduced.

The frame marker

Another way of removing the correlation and frame counting problems is to place the pressure directly on the film frame and number the frames. For ease and flexibility this was done by keying the analog pressure
Figure 11—Pressure is recorded using a Statham pressure gauge and displayed on a channel of the Electronics for Medicine oscillographic recorder. Along with the pressure trace there are two markers, one recording the output of a photodiode-fluorescent screen combination in the pulsed X-ray beam and one redisplaying this and accentuating every tenth pulse to facilitate counting up to the particular heart cycle desired. Each pulse corresponds to the exposure of a cine film frame. A mark also appears on every tenth film frame to ensure trace-to-film correlation.

For manual digitization of the pressures a line is drawn using these markers as a reference, and the point at which the line intersects the pressure tracing recorded in units of height. These values are later calibrated to true pressure. The change-over to semi-automatic digitization involves sampling the recorded pressure waveform at the time of occurrence of the peaks on the marker channel.

CONCLUSION

It should be noted that this system may be useful in other areas where dimensional or geometrical analysis of pictures is desired, e.g., area measurement of plane objects (DAI), or measurement of the shape and size of chromosomes (LPI). In addition, analog data presented as bars in a television picture or as televised graphs or traces may be handled very easily; in the first case automatically through the DAI or, in the second, manually through the LPI. The LPI may also be used to count and mark objects in a picture.

Lastly, the entire computer system is available as a general purpose laboratory data acquisition and processing system. We have used it for regional myocardial blood flow measurements, for the processing of Xenon washout curves from the lungs, for statistical analysis, for plotting, for digitizing selected television lines and for the analog-to-digital conversion of electrocardiograms.

Using the television/computer system we have processed, in a 3½ month experimental run, the pressures and dimension data from one complete cardiac cycle (60-100 frames) for each of 80 patients. Other routine studies are under way on both normal left ventricles and on pre- and post-operative left ventricular function. The Cardiovascular Unit at Toronto General
Figure 14A—Mrs. M's ventricle exhibits very poor contraction, a more rounded shape (more spherical than cylindrical) and relatively no change in the long axis length or widths perpendicular to this axis.

Figure 14B—Mr. T's ventricle has excellent left ventricular contraction, an elongated shape (more cylindrical than spherical) and major changes in the long axis and widths.

Figures 14A and 14B—Geometry. Four frames from a left ventricular cineangiogram are shown, one at the end (end-systole) and one at the start (end-diastole) of the cardiac contraction cycle and two intermediate.

Hospital averages 6 investigations per day. We have thus been able to process roughly 20 percent of the cases available at the Unit. Using the hand techniques for measuring volume, we would have been able to process (obtaining volumes only) less than 5 percent of the available cases. It is projected that we will be able to process 50-75 percent of the available cases with the total implementation of the light pen interface and the numerical pressure indication system. This increase can be achieved without the addition of any staff, and with no additional expenditures on hardware. Furthermore, the system will be capable of providing more advanced information to the clinical staff than is currently available.

RESULTS

To illustrate the kind of information generated by the system the results of studies done on 2 patients, one with very poor left ventricular function and one with excellent left ventricular function, are shown in Figures 14-19. Figure 14 shows that the poorly contracting ventricle exhibits little change in all dimensions (width, length and area), whereas the normal ventricle, shows marked reduction in its dimensions. Figure 15 illustrates that the left ventricular widths are larger and show little change from the start to the end of contraction in the poor ventricle compared to the normally contracting ventricle. Similarly, in Figure 16, the poor ventricle's volumes are larger, the rise time slower, and variation smaller in contrast to the normal left ventricle. The pressures (Figure 17) show a slower rise time and a higher minimum pressure in the poor ventricle compared to the good one. The pressure-volume correlation shown in Figure 18 demonstrates that the stroke work (i.e., the work done in ejecting blood) is much smaller in the poorly contracting ventricle, that this work is done at a higher pressure in a
Figure 15A—It should be noted in Mrs. M's width plots, that the values are large, that there is little change from end-systole (small widths) to end-diastole (large widths), and that the rise times are slow. The width at the base of the heart (the top, width 1) shows relatively better contraction compared to the other two widths. Width 3 (at the apex) is out of phase with number 1. These findings are in keeping with the visual findings of a lack of contraction in this area.

Figures 15A and 15B—Width plots. The plot of three widths from the left ventricle at $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of the way along the long axis.

larger chamber, and that little blood is ejected. This means that the poor ventricle has a mechanical disadvantage relative to the normal ventricle. Finally, the wall tension (Figure 19) starts higher, rises more slowly, and remains higher longer in the poor ventricle compared to the good one, indicating that the poor ventricle uses more energy to do less stroke work.

Accuracy in these studies

The accuracy of the measurements of the left ventricle is most affected by picture quality, e.g., if the border of the left ventricle is blurred, the position of the edge cannot be precisely determined. Various arbitrary criteria may then be used to determine the edge automatically and each will produce different measurements of the size of the left ventricle. For this reason, we have chosen to rely on the eye to choose the border. The eye is superior to the machine in recognizing the boundary since it is very sensitive to small changes in contrast and since it uses the whole picture to assist in judging the border. This is put to use in the LPI and in the making of cutouts or the selection of the threshold when using the DAI.

The DAI, when measuring films and cutouts from films of model ventricles, was generally within five percent of the true volume of the model. In routine X-ray films, however, the measured size of the ventricle is very dependent on the threshold chosen. In these cases, the eye must be used to judge the position of the border.

But, even the eye may find it difficult to choose a border, since the border may be very unsharp or irregular due to poor mixing of the radio-opaque dye and the non-uniformities of the wall itself. Some of these problems may be resolved by better injections, improved picture quality, more understanding of the attenuation of the X-rays by the contrasted heart, and more knowledge of the behavior of the left ventricular wall irregularities (trabeculae carneae and papillary muscles) during the heart cycle. Work needs to be done in all of these areas to improve the accuracy and meaning of the results obtained. This is particularly
Figure 16—The volume curves. It should be noted that these curves are displayed on one sheet for convenience only and that they are not in phase, since the two hearts are beating at different rates.

Mrs. M’s (#1) ventricular volumes are large and there is little change in volume during contraction. The rate of change of volume is slow and the usual characteristic features of volume changes during a heart cycle are not evident.

In Mr. T’s (#2) curve there is a large change in volume with a good rise time. Although noisy, the curve seems to show a rapid-filling phase (frames 15-20), a reduced-filling phase (frames 20-27), atrial systole (the contribution of the contraction of the atrium) (frames 36-43) and an ejection phase (frames 43-60). These features are not apparent in Mrs. M’s ventricular volume plot.

Figure 17—Pressure plots. These are the pressure tracings for the two ventricles. The curves are not in phase. The features that are important are: Mrs. M’s peak pressure is lower than that of Mr. T, whereas Mr. T’s minimum pressure is lower than that of Mrs. M. The higher minimum (diastolic) pressure in Mrs. M’s ventricle is typical of a large, dilated, poorly contracting ventricle. Mrs. M’s pressure rise is more gradual, indicating a more poorly contracting ventricle than Mr. T.
Figure 18A—The main features of Mrs. M's loop are that its area, which is proportional to the stroke work, is small. The volume of blood ejected relative to the volume of the cavity is small. Moreover, the centroid of the loop is shifted upward (high pressure) and to the right (high volume) compared to a normal ventricle.

Figures 18A and 18B—Pressure-volume plots. Smoothed pressure-volume plots for Mrs. M and Mr. T.

true now, as we would like to measure wall thickness accurately.

Other errors in left ventricular measurements arise from changes in the X-ray system magnification (image intensifier), spatial distortion by the intensifier, film shrinkage, human error in outlining and cutting out the paper for the cutouts, the spatial orientation of the left ventricle when it is filmed, and the orientation of the cutout while being measured. Studies of these errors are in progress and techniques will be refined to reduce them.

FUTURE OBJECTIVES

The light pen and light pen interface are becoming operational on a routine basis. This speeds the processing time, allows more cycles per patient to be done, and provides more information per frame (the coordinates of the border are available and hence shape may be measured). With the ability to process a larger number of heart cycles per patient, we should be able to study the stressing effects of drugs and other inotropic agents, such as pacing, within a given angiogram or by repeat angiograms. This should provide further information about the functional state of the left ventricle.

Meanwhile, a systematic study of the X-ray system and other factors affecting border recognition is being pursued. This should eventually provide us with better quality pictures.

A number of projects are under way in the development of the television/computer system:

(1) We will attempt to improve the automated system (DAI) by using more reliable border recog-
nition criteria (presently merely voltage threshold sensed by a Schmitt Trigger) and also by enhancing the image presented to it, finally perhaps carrying out rapid measurements on videotape recordings and displaying the results during the catheterization.

(2) We are planning a more efficient semi-automated system involving improvements to the LPI and the use of the DAI in conjunction with it; for example, the LPI can be used to delineate areas to be quickly and automatically measured by the DAI (the left atrium and aorta may be cut off using the LPI, and the left ventricle measured by the DAI).

(3) More use of automation in the handling of analog data is being attempted.

(4) We are considering the development of a video-densitometric system to provide two important measurements: (a) of the blood flow, and (b) of the depth of opacified objects (assuming that the density of an image is due to the depth of absorbing material in the path of the X-rays).

Presently, the system is being assessed as to its usefulness in the clinical and biophysical studies now being carried out. It has, however, already been valuable in providing clinical data in the Cardiovascular Unit and may have many applications for measurements on pictures and analog signals elsewhere within the hospital, in research, and in industry.

ACKNOWLEDGMENTS

The authors are grateful to the technical staff of the Department of Medical Engineering and Biophysics, particularly to Mr. Paul Mendler for his work on the DAI and LPI, to Mr. Roy Liggins for his excellent technical assistance, to Mr. Donald Mills for constructing the DAI, to Mr. Robert Kubay for building the trace marker circuits, to Mr. Robert Growcock for the digital number display construction, and to Mr. Franz Schuh and Mr. Louis Rostocker for their mechanical assistance. In addition, the authors would like to express their appreciation to Mr. Eric Covington for his contribution to the programming, to Mrs. Yasna Polic, Mrs. Ulla Nordin and the Department of Art as Applied to Medicine for the diagrams, to Mr. Barry Bassett for the photographs in Figures 6, 10 and 13, to the Department of Medical Photography, Toronto General Hospital for photographing the figures, and to Miss Vivian Martin for her excellent secretarial assistance. This work was supported by the Ontario Heart Foundation and Toronto General Hospital.

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