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# Left Ventricular Videometry*

PAUL D. CLAYTON, LOWELL D. HARRIS, STEVEN R. RUMEL, AND HOMER R. WARNER

*Latter-day Saints Hospital, Cardiovascular Laboratory, Salt Lake City, Utah 84143*

*and*

*Department of Biophysics and Bioengineering, University of Utah, Salt Lake City, Utah 84143*

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To quantitatively describe left-ventricular dynamics, a computer is used to process video angiocardiographic recordings. A special interface for transferring the video information to the computer and a border definition algorithm are used to automatically obtain the border coordinates of the ventricular chamber for each video field (1/60 sec) during systole. For each point in the digitized picture matrix, the probability that the point should be designated as the border is computed. This probability is the product of four separate border definition criteria. The computer determined borders are in good visual agreement when superimposed upon the original video images.

## INTRODUCTION

A knowledge of the left ventricular dynamics during systole is of utmost importance in assessing the level of performance of the cardiac pump. As Hawthorne (*1*) has stated, "The emergence of the concept that left ventricular performance can perhaps best be described in the terms of muscle mechanics, has stimulated circulatory physiologists to acquire a more precise description of the dynamic geometric changes occurring in the left ventricle with its contraction and relaxation."

The most popular method used to study cardiac dynamics is cine and video-angiocardiography because it allows the investigator to view directly the shape and motion of the cardiac silhouette. The benefits of angiocardiography as a diagnostic tool can be enhanced by using a digital computer to process the large volume of data contained in an angiographic recording. Automatic processing greatly facilitates quantitative description of ventricular dynamics. The purpose of this paper is to describe a special computer interface system and border algorithm developed to quantitatively evaluate the dynamic geometry of the left ventricle.

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## System Description

During routine diagnostic catheterizations as well as dog experiments, high contrast angiograms are obtained by injecting radiopaque dye into the left ventricle (LV). An X-ray image intensifier and video image orthicon camera (*2*) are used to convert the dynamic roentgenographic image into an analog video signal. While this angiocardiographic sequence is being recorded on video tape and/or video disc, pressure and electrocardiographic signals are sampled by a digital computer to permit later synchronization of the video and physiological data. The video information is transferred to the computer for border recognition processing and the computer determined ventricular border coordinates for each successive video field are used to quantitatively analyze left ventricular function during systole.

Before the video information can be processed in the computer, the analog signal must be digitized. Central to the problem of real-time quantization of a video angiogram are the high data rates and large storage requirements. For example, if the video level is sampled at 256 points per TV line using a 10 bit A–D converter, the digital information corresponding to an angiogram of 5 sec duration exceeds $10^8$ bits. The data rates required to sample 256 points in 50 $\mu$sec ($5 \times 10^7$ bits/second) are not compatible with a general purpose time-sharing computer (*3*).

To accomplish sampling under the constraints of our system, a column video digitizer was designed to sample data from the same video field displayed repeatedly by a video disc operating in the "stop action" mode. The video disc (Ampex Corp., Model DR-10A) in use at the Latter-day Saints Hospital has factory modifications which allow the computer to read the video field address and to actuate the disc controls. Thus, the disc can be set to a given frame and video information can be recorded or played back under computer control.

To achieve maximum contrast of the radiographic image and to optimize ventricular mixing, the computer is programmed to control the dye injection by analyzing the ECG rhythm. This assures that for normal heart rhythms, the initiation of dye injection will occur during early diastole. The computer puts the video disc recorder in the "record" mode at the same instant the dye injection syringe is triggered. The computer samples, via an analog-to-digital converter, the physiological variables (ECG, LV pressure, and aortic pressure) and stores them in conjunction with the disc field count of the corresponding video information. Angiocardiograms are recorded in parallel on video tape and can be transferred to the disc for later processing. Correlation between the physiological variables and video information is maintained by multiplexing and recording the physiological data on the audio track of the tape.

The field addresses of the images corresponding to end diastole and end systole are computed by finding the onset of the rise in ventricular pressure and the dicrotic notch of the central aortic pressure (*4*). Under computer control, the video digitizer

then automatically digitizes successive video fields until all images obtained during the systolic portion of the cardiac cycle have been processed.

## Video Digitizer

A computer-interactive system (*5*) has been built for selectively converting a video level at any point in a picture to a 10 bit number and transferring that value to a computer. Three 12 bit digital input lines to the computer and two 12 bit output lines provide for communication between the digitizer and the computer. A coordinate system is used to relate the time varying analog video signal to the geometrical TV image. The location of a point is referenced to a cartesian coordinate system whose origin is in the lower-left corner of the picture. The vertical ($y$) coordinate corresponds to the video raster line count and is stored in a register which is set to 255 by the video vertical sync pulse and is decremented by the horizontal sync pulse at the end of each raster line. The horizontal ($x$) coordinate is derived from a counter which is clocked at 5 MHz (256 increments/52.5 $\mu$sec) and is reset to zero at the beginning of every line by the horizontal sync pulse.

To achieve maximum flexibility and efficiency with the time-shared computer, the video picture is digitized column by column. Using a digital output word, the computer gives an $x$ coordinate, a field specification, and a "memory fill" command to start a column digitize cycle and then relinquishes control. It is this independent fill cycle and a buffer memory which make the digitizer compatible with a time-shared computer. On each television line when there is coincidence between the computer specified $x$ coordinate and the clock counter $x$ coordinate, a "sample" pulse is generated which causes the video level to be "held" for analog-to-digital conversion. Because it operates in the "column" mode, the digitizer has 63.5 $\mu$sec (horizontal sweep time) to perform a 10 bit analog-digital conversion and store the quantized video level in an addressable read/write 256 word buffer memory. The $y$ coordinate (line count) is the buffer storage address for the quantized video level information. After waiting 1/20 sec to allow the digitizer to sample the entire column at the computer specified $x$ position and field, the time-shared computer returns control to the program controlling this process. It then reads the quantized video levels from the buffer memory by specifying to the digitizer the desired $y$ coordinate with a digital output word. After the appropriate portion of the buffer memory has been transferred, a new $x$ coordinate (i.e., column position) is specified under program control and the cycle is repeated until the digitized image matrix is complete. It requires 12 sec to quantize a complete (256 by 256) image, but in most cases the image is smaller than this (see below).

Figure 1 is a block diagram of the digitize section of the video quantizer. After a "fill command" and field address are given, the coordinate section (not shown in the diagram) determines when the first line of the selected field is played back from the video disc. A pulse is then generated which sets the $y$ coordinate counter to 255,

and allows the $x$ coincidence pulses to be gated into the sample-and-hold control flip-flop from the memory control board. The memory control board addresses the buffer memory using either the $y$ counter coordinates or the computer specified coordinates. The memory control address mode and read/write mode are determined using the 255 pulse.

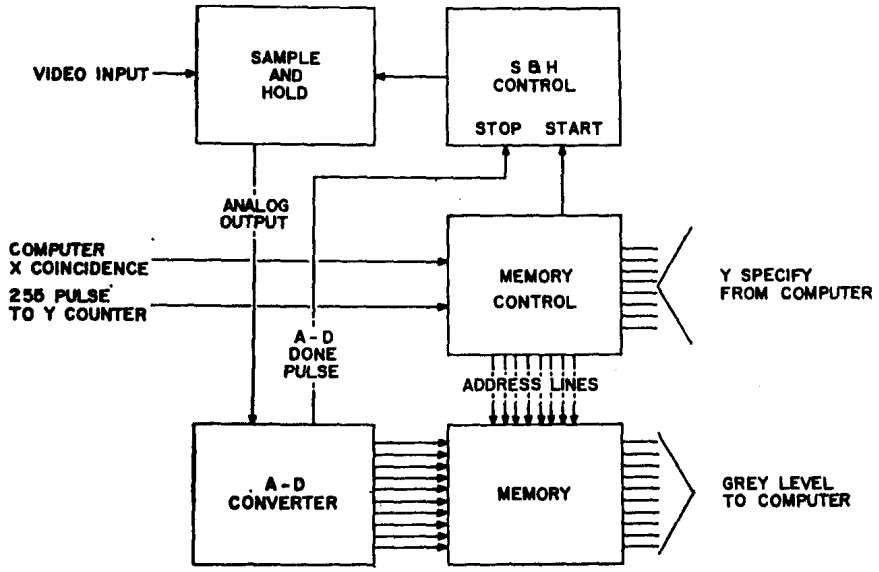


FIG. 1. A block diagram of the digitize section of the video quantizer.

Figure 2 illustrates the timing sequence of the digitize cycle. The gated $x$ coincidence pulse causes the sample-and-hold to maintain the video level while the A–D conversion takes place. The A–D done pulse from the analog to digital converter

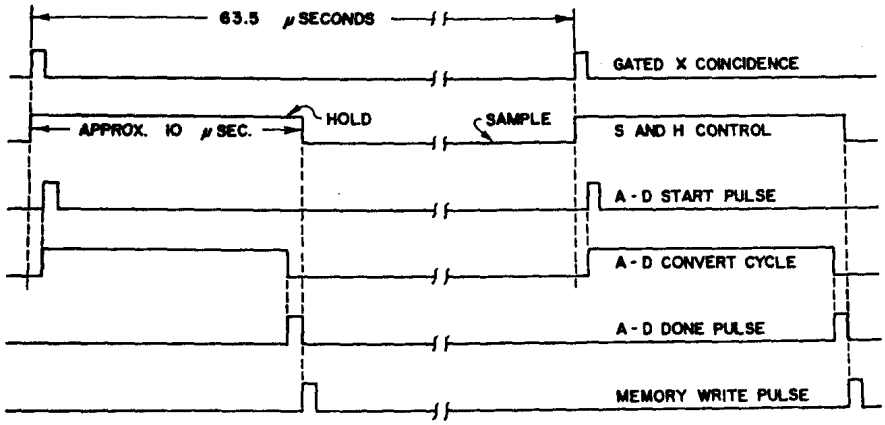


FIG. 2. Digitizer interface timing diagram.

resets the sample-and-hold control to the sample mode and causes the digital value to be stored. The memory counter counts the same gated $x$ coincidence pulses

that initiate the digitize cycle and thereby decrements with every coincidence pulse. The digitized value of the sample on the television line is then stored in the memory cell specified by the memory counter. The gated $x$ coincidence pulses continue to initiate a digitize cycle on every television line at the computer specified $x$ coordinate until all 256 memory cells have been filled. (In practice only 240 of these lines contain usable video information).

The system interface also provides for operator interaction (*6*, *7*, *8*) to allow for program control and to input information related to the video picture. Computer output is superimposed on the video information via a scan converter. Information to the computer is input through a remote terminal keyboard or a table top cursor controller ("mouse"). The position of the "mouse" is indicated by a brightened dot cursor superimposed upon the video picture whenever there is coincidence between the video coordinates and the "mouse" coordinates. The "mouse" coordinates are electronically stored each field, and pushing a "detent" requests the computer to read the cursor coordinates from the buffer register.

This arrangement makes it possible to enter the size and location of the area to be digitized. For example, at the beginning of a sequence of fields the "mouse" is used to mark five points on the image: the right and left sides of the aortic valve, the extreme points on the left and right edges, and the apex. This information is used to determine the orientation of the major axis of the heart and to define the rectangular portion of the image which should be digitized.

## Border Recognition Algorithm

The purpose of the digitizer interface is to quantitize the video information and send it to the computer for ventricular border recognition. Border definition is a complex problem because of the wide variation in image contrast provided by structures other than the dye-filled ventricle, the incomplete mixing of the dye in the ventricle, and the broad range in ventricular shape, size, and orientation. Criteria which identify the border in one angiogram may be insufficient when applied to another. The algorithm is therefore structured to combine various border definition criteria by forming a product. The terms of the product are based on *a priori* assumptions as well as information based on previous lines and fields from the same angiogram.

The border algorithm searches for that point along a line in the quantized picture matrix which has the maximum probability of being the right or left border of the left ventricle. The search can be either along a horizontal or a diagonal line. The probability that a given point should be designated as the border is computed for each point using the product of four independent factors. As explained below, these four terms simulate processes involved in the visual definition of the border. Equation (1) gives the probability that the $i$th point along line $L$ is the right-hand

border of the dye-filled ventricular chamber for that particular line. A similar procedure is used to find the left boundary.

$$\mathrm{PRBR}(i) = \mathrm{GRDR}(i) * \mathrm{VPPR}(i) * \mathrm{LCNR}(i) * \mathrm{SEQR}(i). \tag{1}$$

The coordinate of the right border on line $L$, BR($L$), is the value of $i$ for which PRBR($i$) is maximum.

In Eq. (1), the gradient term [GRDR($i$)] gives information concerning the location of black to white intensity transitions along the line. GRDR($i$) is the moving product of a normal frequency curve and the derivative of the discrete video levels for each point along the line, i.e., a matched gradient filter (*9*). The maximum value of GRDR($i$) will occur where the set of points most closely fits the normal curve assumed for the gradient at the border. The matched filter output is more reliable than a simple point-to-point gradient because the border often has a gradual intensity change which can only be distinguished from electronic or physiological noise by using the information from adjacent points. The Gaussian matched filter used when the sampling density is 256 points/line has a standard deviation of three points and the number of filter points is 20.

The gradient matched filter is generally the strongest border criterion and is the only predictor which is not dependent upon previously determined border points. The matched filter output by itself, however, will occasionally define the border to be at the outer wall of the myocardium rather than the inner wall. Problems occur when the direction of search for the gradient runs nearly tangential to the border or when the left and right borders are very close together at the apex. The tangential problem is alleviated by searching the digitized matrix at a 45° angle rather than along a horizontal line whenever the major axis of the heart image is tilted more than 22½° from vertical. The apex problem is solved by changing to a simple gradient term whenever the distance between right and left borders is less than 15 points.

The term VPPR($i$) (Video Profile Predictor) which appears in Eq. (1) compares the video levels of the ten points on either side of any point $i$ with the weighted values of the video levels adjacent to the determined border on previous lines. This term not only predicts the video level at the border point from the video level at previous border points, but also predicts the video intensity profile at the border from the profile shape at borders on previous lines. Mathematically this can be expressed

$$\mathrm{VPPR}(i) = \left( \left[ \sum_{j=1}^{20} |\mathrm{AVLEV}(j) - \mathrm{LEV}(i+j-10)| * \mathrm{W}(j) \right] + K1 \right)^{-1}. \tag{2}$$

AVLEV($j$) is the weighted average of a sequence of video levels for ten points on either side of the border found on the previous lines. AVLEV($j$) is updated after the border is found on each line according to Eq. (3) for values of the index $j$ between 1 and 20.

$$\mathrm{AVLEV}(j) = (2\mathrm{AVLEV}(j) + \mathrm{LEV}[\mathrm{BR}(L) + j - 10])/3. \tag{3}$$

In Eqs. (2) and (3), the term LEV($i$) is the video level at the $i$th point on the current line. W($j$) equals $j + 10$ for $j < 10$ and $30 - j$ for $j > 10$; these weights are determined empirically. BR($L$) is the index of the right border on line $L$ and $K1$ is an empirical constant which determines the sensitivity of the video profile predictor term in the probability product. This term is valuable in helping the matched filter distinguish between the gradient peaks which occur at the outer wall of the myocardium as opposed to the inner chamber wall. The term is occasionally misleading where ribs or catheters cross the heart border.

The location term [LCNR($i$)] is based upon the assumption of a smooth and continuous border from line to line. The predicted border location for line $L$ is based upon the direction computed from the border position on the previous two lines [BR($L$-1) and BR($L$-2)].

$$\text{LCNR}(i) = (|2\text{BR}(L\text{-}1) - \text{BR}(L\text{-}2) - i| + K2)^{-1}. \tag{4}$$

Again, the constant $K2$ is an empirically adjusted weighting factor. The location term is useful in areas of poor mixing where it is very difficult to determine the border even visually without interpolating between lines.

The time sequence term, SEQR($i$), predicts that for a given line the location of the border in the current video field should be dependent upon the temporal movement of the border in the two previous fields ($T$-1 and $T$-2). For a given line, the absolute difference between the predicted border location for the present field and any point $i$ on that line is calculated. This difference is added to the weighting constant $K3$ as shown in Eq. (5).

$$\text{SEQR}(i) = (|2\text{BR}(T\text{-}1) - \text{BR}(T\text{-}2) - i| + K3)^{-1}. \tag{5}$$

This term makes use of the fact that the muscle contraction should be smooth and monotonic. In the first video field where this term is not available because there are no previous borders defined, corrections to the contour can be manually entered. This corrected contour is then used to provide the sequence term, and the border for this field is recomputed.

For any field, manual corrections can be made if the computer does not determine an acceptable border. This option is not frequently needed, but does provide necessary flexibility. The apex is defined by requiring that the borders cannot move outward whenever the left and right borders are within 15 points of each other. When the borders cross or are within two points of each other, the apex is closed. A nine-point parabolic smoothing algorithm (*10*) is applied to the contour, and then the base of the heart (aortic valve) is located. This is accomplished by searching for the minimum distance between any of the first 20 points on the left border and any of the first 20 points on the right side.

## EVALUATION

Quantitative evaluation of the success of a border algorithm is difficult after the algorithm is no longer generating errors that are obvious when a plot of the border coordinates is superimposed over the original image on the TV. One approach to an objective measure has been tried by comparing the computed border to a border determined by a cardiologist. The cardiologist moves a cursor around the left ventricular image border using a "mouse" to control the cursor. The two borders are then superimposed on the TV monitor for comparison. The resulting differences

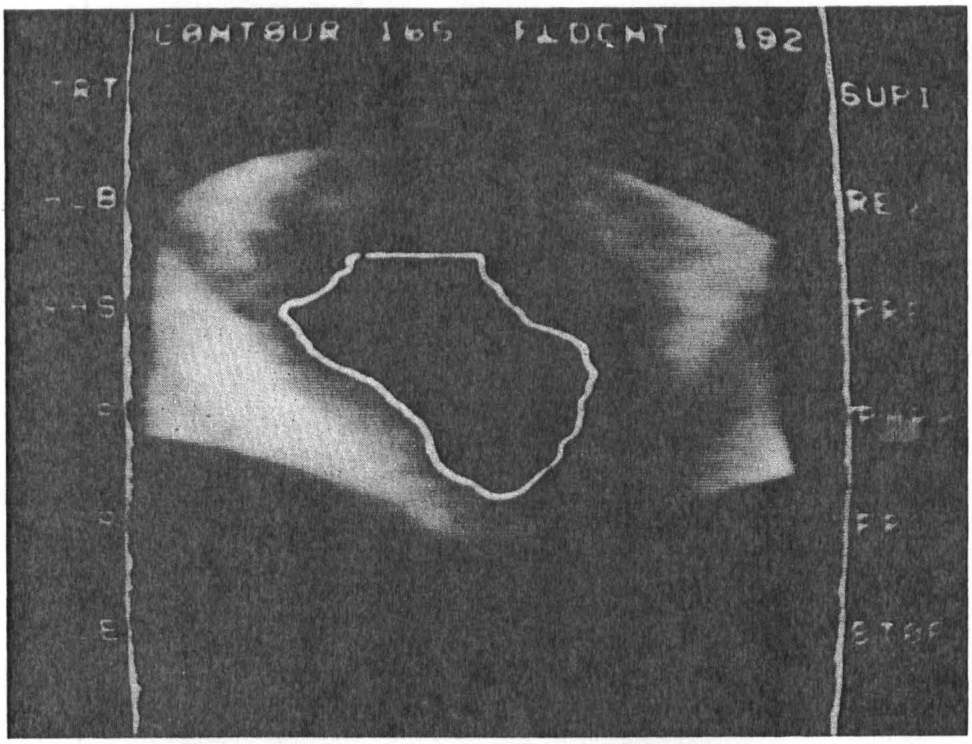

FIG. 3. A computer determined ventricular border. The results of the automatic border recognition algorithm are superimposed upon the image of a dye filled canine left ventricle. The instructions on either side of the picture represent the program options. These options can be selected by moving the "mouse" cursor dot which is seen near the field count display at the top of this picture.

are small and the manually input traces, when repeated, have more variability than do repeated computer determined contours. This is especially true when different people enter the manual trace.

The superimposition of a computed contour on the video picture is illustrated in Fig. 3, while Fig. 4 shows the same frame without the computer-determined contour. The visual comparison is complicated by the fact that the monitor display is comprised of two fields (1 frame) which were not recorded at the same time. This visual

agreement of the superimposed contour with the video picture in hundreds of images has given confidence that the border algorithm does indeed perform satisfactorily. In addition, many computer plots of video level as a function of time for a single line have been generated which also contain individual plots of the four terms and their product (Fig. 5). This provides additional insight into the performance of the algorithm and, indeed, played an important role in determination of appropriate values for the weighting factors.

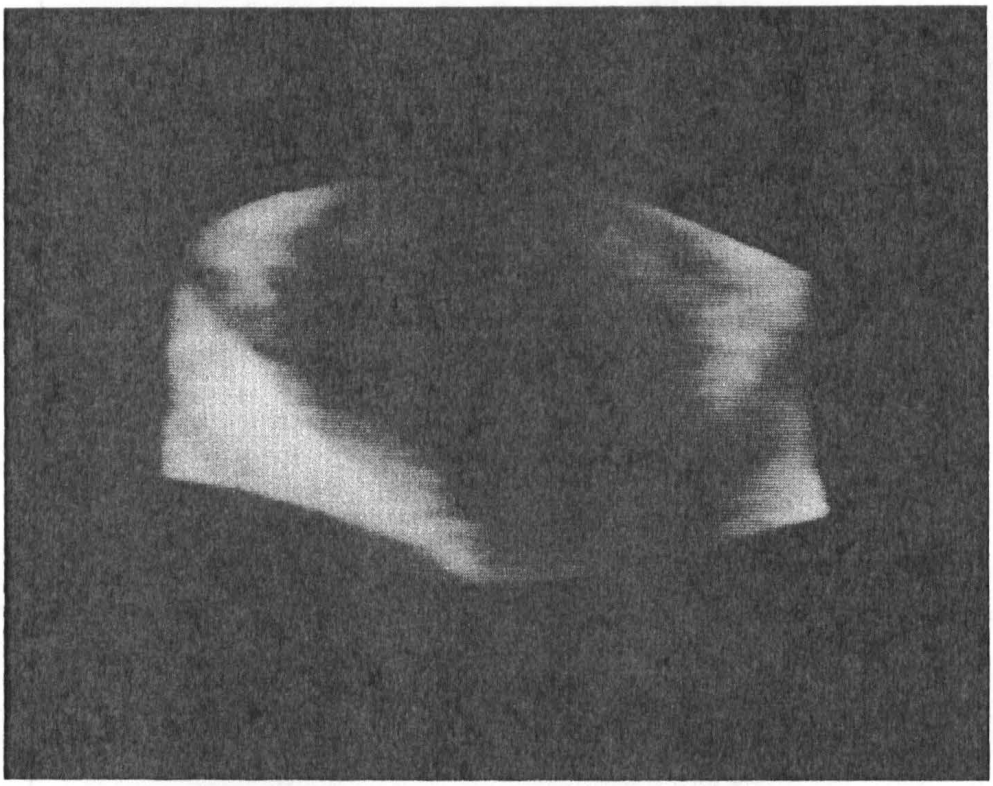

FIG. 4. The video roentgenographic image of dye filled canine left ventricle without the superimposed contour. The monitor image is obtained using a stop action video disc recorder.

An additional indirect check can be made using the computer cross-sectional ventricular areas. During systole this area becomes smaller for every sequential field, which shows that there is reproducibility of the algorithm as the shape and volume change. In quantitative evaluation of the myocardial performance, it is really this reproducibility of the border algorithm which is most important, since all measurements are calibrated using known dimensions and normalized.

## SUMMARY

The border algorithm has been used successfully on both human and canine angiograms. Using the "automatic" feature of the program, one can enter the address of the first field of systole and the total number of contours to be computed.

After manual entry of five boundary points which define the rectangular area of the image to be digitized, the entire systolic sequence (approximately 20 fields) is processed completely automatically. The computer processing time is 55 sec per field; thus a sequence can be processed in 15 to 20 min.

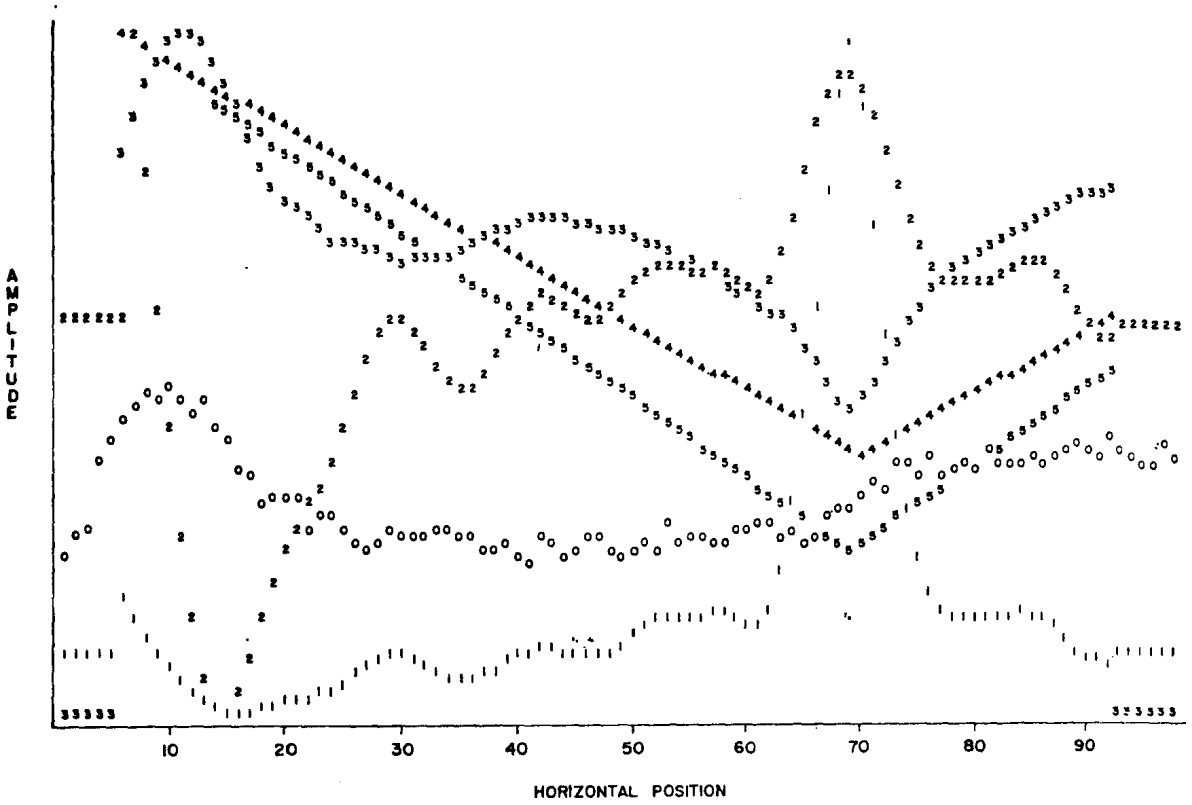


FIG. 5. A plot of the terms used to determine the right border coordinates of the ventricular chamber. The zeros represent the digitized intensity levels from left to right along a single TV line. The larger amplitudes correspond to the brighter levels of the picture. The ones represent the probability term [PRBR(I)] defined as the product in Eq. (1). The two's show the output of the gradient matched filter. The remaining symbols represent respectively the inverses of the (3) video profile predictor [VPPR(I)], (4) location [LCNR(I)], and (5) time sequence [SEQR(I)] terms.

The computer-determined ventricular border does accurately coincide with the visual information and these borders are adequate for describing ventricular wall motion in a single plane. This quantitative information, when used to define parameter values for a model (11) of ventricular motion, should be valuable in evaluating patients being considered for coronary artery surgery or in assessing the time course of their disease.

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