REPORT R-587 SEPTEMBER, 1972 UILU-ENG 72-2249

CSL COORDINATED SCIENCE LABORATORY

COMPUTERIZED OUTLINE DETECTION OF MAJOR ORGANS IN THE CHEST X-RAY

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Coordinated Science Laboratory University of Illinois Urbana, Illinois 61801	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP
3. REPORT TITLE COMPUTERIZED OUTLINE DETECTION OF MAJOR ORGANS IN THE CHEST X-RAY	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)	
5. AUTHOR(S) (First name, middle initial, last name) Richard Hagop Koomjian	
6. REPORT DATE September, 1972	7a. TOTAL NO. OF PAGES: 50 7b. NO. OF REFS: 13
8a. CONTRACT OR GRANT NO. DAAB-07-67-C-0199 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) R-587 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) UILU-ENG 72-2249
10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited.	
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Joint Services Electronics Program through U. S. Army Electronics Command

13. ABSTRACT

The chest X-ray photograph is one of the most widely used diagnostic techniques for the early detection of lung and heart diseases. It is one of the few diagnostic tools which can be administered to the broad cross-section of the population. The greatest restriction to its use for widespread early detection of disease is not in the administration of the chest X-ray, but in its diagnosis. If a machine were capable of making a preliminary evaluation of the contents of a chest X-ray, it could screen out X-ray photographs which possibly contain indications of disease from those which appear to be normal. Then skilled technicians could concentrate their time on carefully examining a smaller number of X-rays which would be more likely to contain heart or lung pathologies.

Details of illustrations in this document may be better studied on microfiche

1a

DD FORM 1 NOV 65 1473

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Computerized diagnosis						
Chest X-rays						

UILU-ENG 72-2249

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This work was supported by the Joint Services Electronics Program (U. S. Army, U. S. Navy and U. S. Air Force) under Contract DAAB-07-67-C-0199.

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OF MAJOR ORGANS IN THE CHEST X-RAY

BY

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B.S.E.E., Illinois Institute of Technology, 1966

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1972

Urbana, Illinois

ACKNOWLEDGEMENTS

The author wishes to express his deepest appreciation to Professor Franco Preparata for his advice and cooperation in the conduction of this research. The author also thanks the members of the ILLIAC III group for their assistance in preparing a digitized image and to Mrs. Sharon Page for her patience in typing this manuscript.

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1. INTRODUCTION

The chest X-ray photograph is one of the most widely used diagnostic techniques for the early detection of lung and heart diseases. It is one of the few diagnostic tools which can be administered to the broad cross-section of the population. The greatest restriction to its use for widespread early detection of disease is not in the administration of the chest X-ray, but in its diagnosis. If a machine were capable of making a preliminary evaluation of the contents of a chest X-ray, it could screen out X-ray photographs which possibly contain indications of disease from those which appear to be normal. Then skilled technicians could concentrate their time on carefully examining a smaller number of X-rays which would be more likely to contain heart or lung pathologies.

The work described in this paper is one facet of a project which addresses itself to the difficult problem of creating techniques which will enable machines to examine chest X-rays for the possible detection of abnormal heart or lung conditions. This paper describes a technique for computerized detection of the outlines of the heart and lungs. This is an essential step in the diagnostic process for two reasons. First, to examine the lungs for possible lesions or unusual textures, the region of the lung must be known. Second, abnormal shape or size is frequently a symptom of heart or lung pathology. (Examples of this are forms of rheumatic heart disease.[3,4])

Much work has been reported in the literature concerning aspects of the problem of computerized diagnosis of X-ray photographs. Hall, et al. have described techniques for image enhancement of the X-ray[5,6] and objective measures have been established by which the results of various enhancement techniques may be compared.[2]

At least two methods have been described for partitioning the chest X-ray into the regions of the major organs. Sutton and Hall[12] identified the regions of the lungs in order to make texture measurements. The technique they employed was a modified thresholding procedure. The area of the X-ray was divided into small overlapping regions. A grey level histogram was created for each region and if the variance of the histogram was large, the region was considered to contain boundaries (e.g., between the lung and chest wall.) The histogram was assumed to be a mixture of two Gaussian component distributions. The maximum likelihood threshold was then calculated for each region and this spatially sensitive threshold was used to discriminate between the lung regions and the surrounding region. Hall et. al.[4] use essentially the same technique to identify the region of the heart in order to make size and shape measurements.

Harlow and Eisenbeis[7] use a different procedure for partitioning the X-ray into four regions; the left and right lungs, the heart and diaphram region, and the mediastinum region. They use a top-down procedure similar to that discussed by Preparata and Ray.[10] For each region picture coordinates are chosen which are most likely to contain the region. Each region is then "grown" using properties of that region such as brightness, shape, relative size, etc. as descriptive guides. To increase computational efficiency, the regions are first grown using very coarse picture resolution. As the boundaries of the regions approach each other, picture resolution is increased to allow more precise boundary identification. An important feature of this approach is that the feature extraction and pattern recognition phases are interactive.

The approach described in this paper is similar to the technique of Harlow in that emphasis is placed on an interaction between the scene analysis and feature extraction procedures. This approach utilized the simple, reliable semantic structure of the PA chest X-ray, but it is hoped that this appraoch is general enough for application to other scene analysis problems with a simple semantic structure.

A top-down search from the most general objects to their details is employed. This is accomplished in four steps.

1. The location of the centers of the major organs are determined.
2. A description of each organ is compared with the X-ray image to form a coarse outline of the organ.
3. Feature extraction is performed under the supervision of the coarse outline.
4. Final estimation of the organ outline is based both on local features and a description of the organ.

The most important aspect of this approach is that the most general or global search precedes and guides the local search. The scene analysis phase and the feature extraction phase work interactively to complete recognition of the outline of the organ.

2. BRIEF DESCRIPTION OF APPROACH

A simple block diagram of the equipment used to form the system is shown in Figure 1. The flying spot scanner illuminates the film with a small spot of light which scans the image in a raster motion not unlike the raster display of an image on a television screen. The level of light intensity is measured by a photomultiplier tube circuit and is quantized into sixteen levels. The result of this procedure yields a two dimensional array representation of the original chest X-ray; the area of the X-ray has been digitized into 128 columns and 256 rows to form a 128 x 256 element array, and each array element contains one of sixteen symbols which represents the light intensity of that portion of the original chest X-ray photograph. This array may be called the image array.

The image array is then recorded onto standard computer compatible ½" magnetic tape. All the programs described in this paper were written in FORTRAN '60, run on a CDC 1604 computer, and used this 128 x 256 element image array as the sole representation of the original photograph.

The hardware equipment used to digitize the X-ray information predated the initiation of this project and was used without modification even though in some respects it proved to be less flexible than desirable. First, the existing equipment did not permit the design of detection algorithms which could request selected data from the original image. The image array contained all the input information, thereby excluding an interactive approach to the problem. This meant that at one extreme the image array contained much more detail than necessary for a global or coarse examination, but at the other extreme did not contain the fineness or richness of detail that is present in the original photograph and could

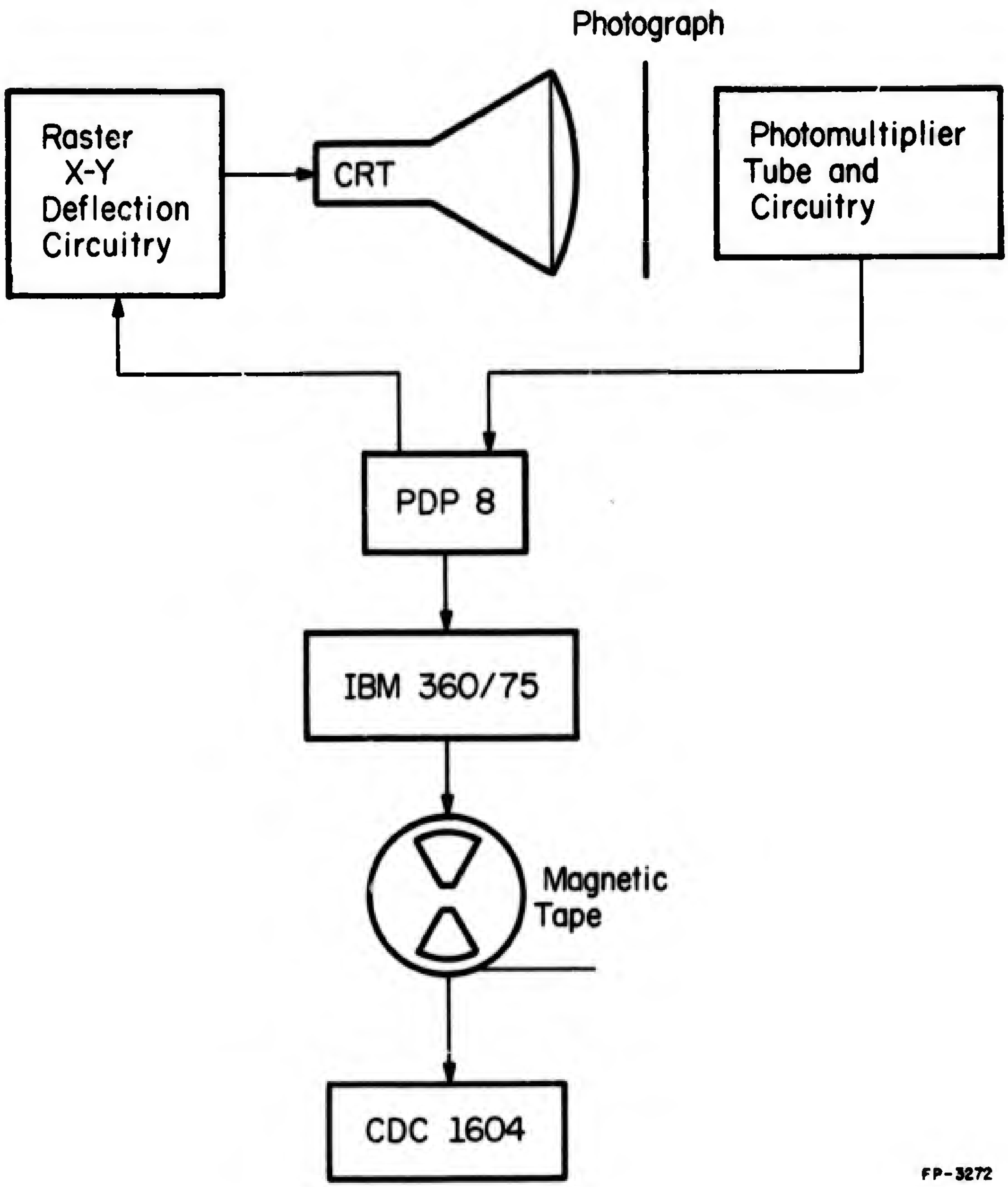

Figure 1

Hardware Organization of System

be useful in edge detection. Also, due to limitations of the optical scanning device, the original chest X-ray was reduced from its original 14" x 17" size to the size of a 35mm film negative. These problems will be discussed further in the conclusion.

The object of this set of programs is to extract the outline of the lungs and heart. After a brief training period the human eye becomes very competent at extracting outlines of these organs. One of the most important features of the edge is the rapid spatial rate of change of light intensity which appears visually as a line. After examination of an X-ray one might conclude that the edges may be obtained by processing local information (that is, by making measurements over a relatively small area or patch of the overall picture image.) The lung is a dark, coarse shadow which is surrounded by very light areas. On one side is the rib cage and on the other are the regions of the spine, heart, and abdomen. Likewise the heart is boardered on the left and right by the lungs but fades indistinguishably into the spinal region above and into the abdominal region below.

Since the rate of change of light intensity is such a strong visual clue to the human eye, it is natural to consider using the same clue in machine recognition. An algorithm could be created to use this property to extract the edges of the major organs by a spatial differencing operation performed repetitively on various portions of the image array. This method was in fact attempted. A program was written which would search for the lung edge in three adjacent neighborhoods. These neighborhoods were selected where the edge would be distinct and reliable from one X-ray to another. Then using a smooth curve extrapolation of points where the edge had been detected in these regions, the program would generate a new region which was very likely to contain another segment of the edge. Repeating this sequence of steps it was hoped that the algorithm would "walk" around the organ, predicting a new region in which it would be fruitful to search for the edge, then making a local, detailed examination of that area for the edge. It was hoped that the algorithm would search sequentially in regions which would circumscribe the organ. (Testing of this program was done exclusively on the right lung.) Unfortunately this algorithm proved to be unstable. Distracting edges which were irrelevant to the search for the lung edge would be incorrectly interpreted as the real edge. As a consequence the extrapolation procedure would indicate a search region in which there was no lung edge to find.

A major problem to the use of local processing techniques for detecting the edges of the lungs and heart is that the features used for recognition of the "true" edge are often obscured by features of irrelevant edges. This is particularly true of the lung edge. This edge is frequently quite soft (small rate of change of light intensity) and may be obscured by rib edges which are very clear-cut (large rate of change of intensity). The local image features generated by irrelevant edges may be considered "noise" on a semantic level. In the search for the true edge of an organ, these noise features are irrelevant and distracting. This problem is significant because it is almost impossible to distinguish between relevant and irrelevant features when local processing techniques are used exclusively.

It is these facts which lead the investigator to the conclusion that some "global" or semantic guide was necessary to distinguish between semantically meaningful and semantically meaningless information. This scheme would search for image features from the "top down," that is from the most general or global features of the image down to the local features described above.[10,7]

Figure 2 illustrates the steps used to identify relevant image features in three steps from the global level to the local. First, the correlation function is used to find the approximate centroid of the lungs, heart, and claviculae. Second, a standard outline of the organ is compared with the image array. Distortion operators are applied to the standard outline until a "best match" is achieved between the two. At this point the "distorted" standard outline forms a coarse match with the outline of the organ. Points of the distorted standard outline are located near the edge of the organ, and the distorted standard outline is almost parallel to the outline of the unknown edge of the organ. Third, local processing to find the precise organ edge is performed under the guidance of the distorted standard outline.

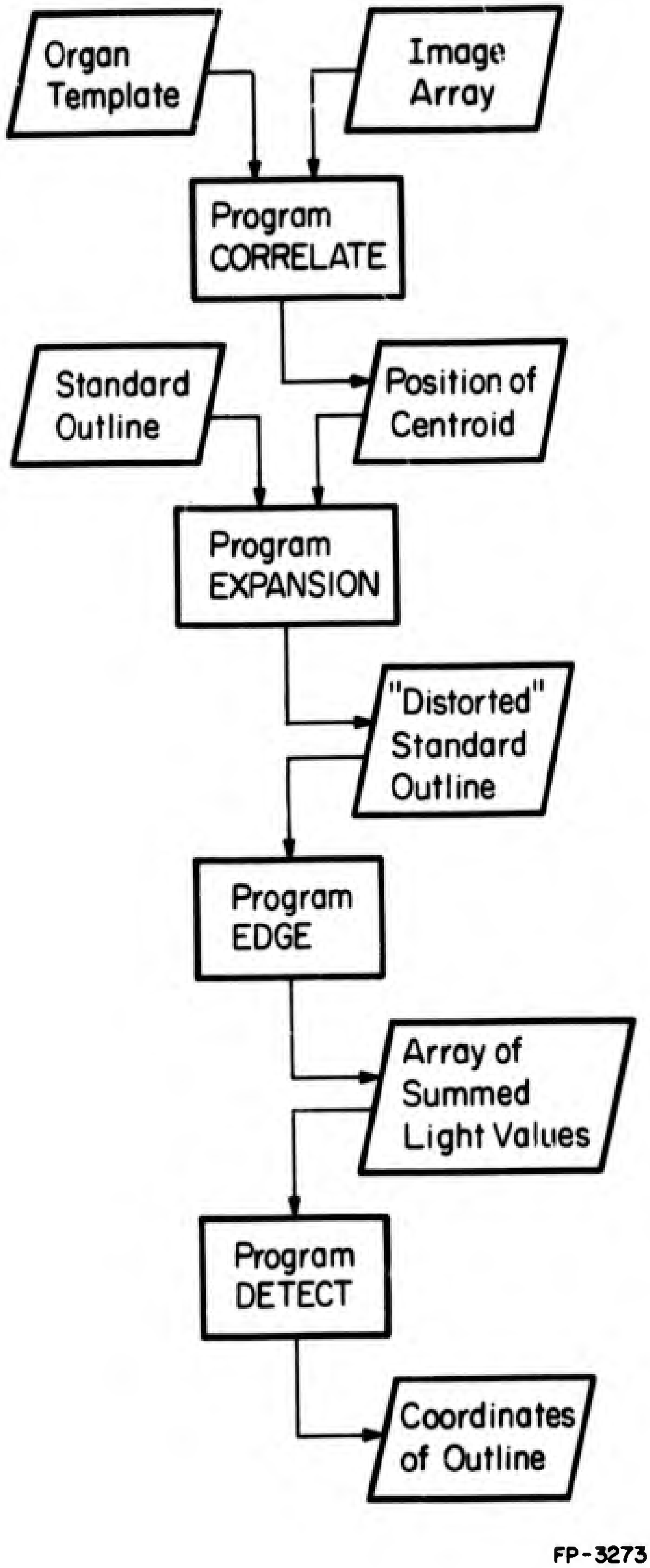

Figure 2

Programs for Outline Detection

3. TEMPLATE MATCHING PHASE

The first facet of this top-down approach for detecting the outline of the major organs is to determine the approximate centroid of the lungs, heart, and claviculae. The correlation function is a powerful tool in arriving at a "best match" between a set of templates or paradigms and an unknown pattern. This is commonly referred to as "classification" of the input pattern. The correlation function can also be used to determine the displacement of a pattern which has already been classified. For example, it is assumed that the dark shadow of the right lung will appear in the left half of the X-ray image, but the position of the centroid is unknown. A sequence of correlations can be calculated between the image array and a lung template over a sequence of differing relative displacements. When the template is at a relative displacement which best superimposes the template over the right lung, the value of the correlation will be at a relative maximum. This can be represented mathematically as follows:

$$c_{ij} = \sum_{i=1}^{m} \sum_{j=1}^{n} T(x-i,\ y-j) \cdot I(x,y) \qquad (1)$$

where T(x-i, y-j) represents the template array at a relative displacement of (i,j) from the image array I(x,y).

An array of the results of the correlations performed at the relative displacement (i,j) can be created:

$$\begin{array}{ccccccc} c_{11} & c_{12} & \cdots & c_{1j} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2j} & \cdots & c_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{m1} & c_{m2} & \cdots & c_{mj} & \cdots & c_{mn} \end{array}$$

This array may be called the correlation array. The value of c_{ij} which is maximum indicates the displacement at which the template is best superimposed over the object. By knowing the centroid of the template it is easy to calculate the centroid of the object. Figure 3 shows a flow diagram of Program CORRELATE used to perform the calculations mentioned above.

In Equation (1) the term T(x-i, y-j) is referring to the template array. The template was created by selecting twenty-eight chest X-rays at random. For each one of these sample X-ray photographs the outline of the heart, lungs, and claviculae were determined visually by the investigator. The template for each organ was created by storing in each element of the array the frequency with which it contained the region of that organ. Figure 4 shows the template of the right lung. A reduced grid of 32 x 64 was used instead of the full 128 x 256 in order to limit the difficulty of creating the template. It was felt that the correlation could be accurately computed based on calculations of only a small subset of the total number of elements in the image array. The final calculations of the correlation function confirmed that 32 x 64 element template array contained more than sufficient detail.

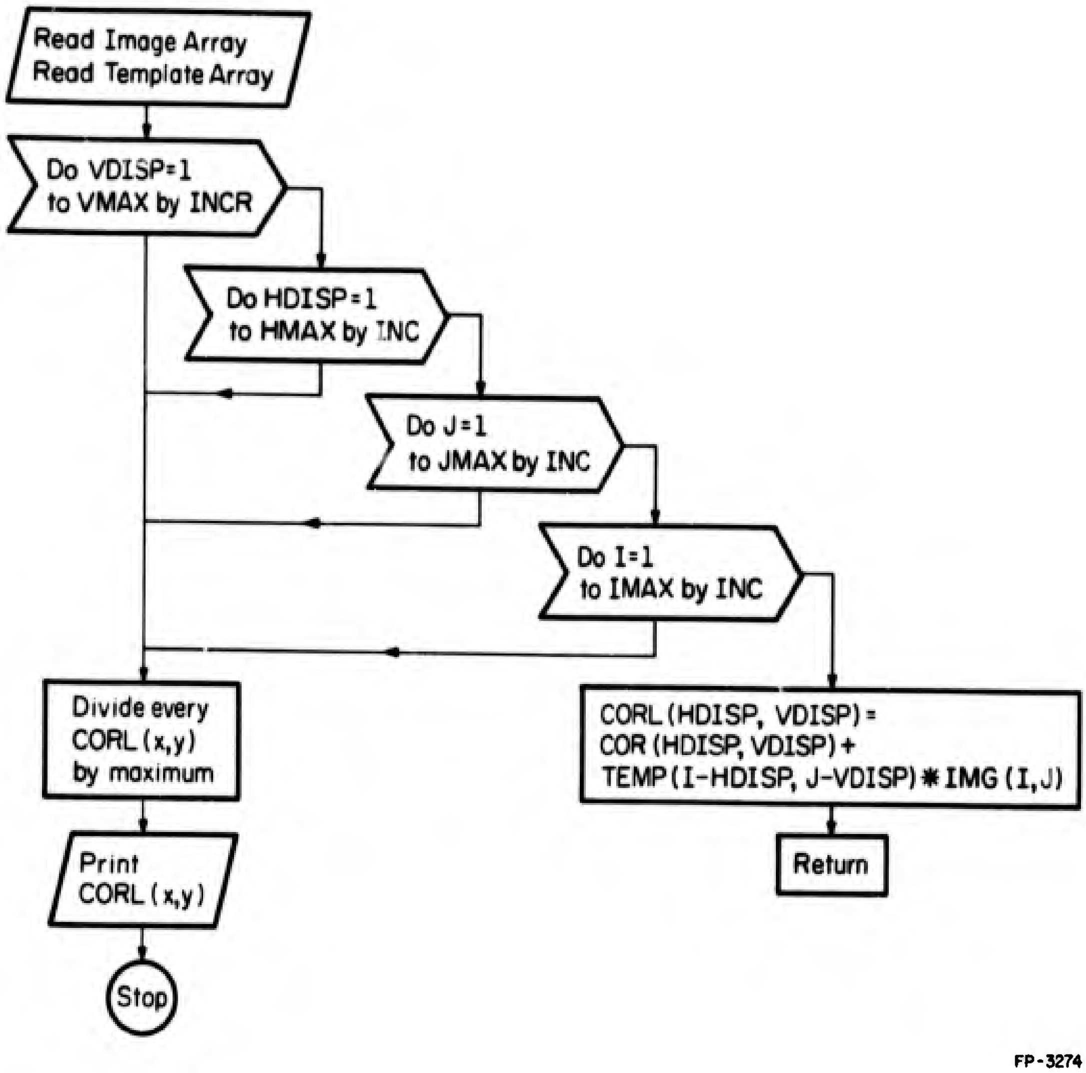

Figure 3

Program CORRELATE

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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3

Right Lung Template

If each point of the image array is used in computing the correlation, the total number of multiplications necessary for each element of the correlation array is:

$$\text{No. of multiplications} = 128 \cdot 256 = 3.3 \cdot 10^4$$

Therefore the total number of multiplications needed to form the correlation array is:

$$\text{Total No.} = 3.3 \cdot 10^4 \cdot m \cdot n$$

The resulting surface (or hill) described by the correlation array is very smooth. This suggests that fewer points in the correlation array are sufficient to determine the maximum by using a parabolic interpolation procedure. What could be done, is to displace the template array by an increment of four units (instead of one unit) in the generation of the correlation array. And to minimize computation, the correlation function might be calculated only on every fourth element horizontally and vertically in the image array. This modified correlation function may be written:

$$c'_{ij} = \sum_{i=1}^{m/4} \sum_{j=1}^{n/4} T(x - 4i, y - 4j) \cdot I(x,y) \qquad (2)$$

The correlation array now takes the form:

$$\begin{matrix} c'_{44} & c'_{48} & \cdots & c'_{4n'} \\ c'_{84} & c'_{88} & \cdots & c'_{8n'} \\ \cdots & \cdots & \cdots & \cdots \\ c'_{m'4} & c'_{m'8} & \cdots & c'_{m'n'} \end{matrix}$$

where $m' = 4\,[\frac{m}{4}]$, $n' = 4\,[\frac{n}{4}]$ and "[ ]" denotes "integer part of."

The total number of multiplications needed to create a correlation array becomes:

Total No. of Multiplications = 125 · m · n

This is a reduction in the number of multiplications by a factor of 256. The following table indicates the reduction in computation for various sampling values:

Sampling Density	Incremental Displacement	Mult. Reduction
1 of 4	4i, 4j	256
1 of 5	5i, 5j	625
1 of 6	6i, 6j	1296
1 of 8	8i, 8j	4096
1 of 10	10i, 10j	10,000

This is not achieved without some sacrifice, however. The error between the precise centroid of the organ (as determined by calculation of the correlation for every element) and the interpolated estimate of the centroid grows with the reduction of calculations. The table below shows the horizontal and vertical average error of three samples of the right lung as a function of the sample density. Error is given in terms of picture elements.

Sampling Density	Horizontal	Vertical
1 of 4	0.25	0.94
1 of 5	0.73	2.40
1 of 6	1.00	2.00
1 of 8	0.73	2.10
1 of 10	2.07	6.20

As a result of these figures, a sample density of 1 of 8 was used to arrive at the approximate center of the right lung. Figure 5 is a typical correlation array of the right lung produced by the algorithm of Figure 3. The array has been normalized by dividing every element by the value of the largest element.

	-4	-3	-2	-1	0	1	2	3	4	5
-5	.120	.225	.349	.456	.542	.588	.603	.591	.541	.460
-4	.136	.252	.380	.495	.580	.627	.641	.623	.560	.481
-3	.159	.281	.416	.533	.617	.668	.676	.649	.576	.492
-2	.173	.303	.449	.576	.656	.706	.712	.677	.598	.506
-1	.191	.331	.479	.610	.699	.745	.744	.704	.617	.519
0	.215	.366	.519	.650	.737	.782	.779	.730	.634	.529
1	.238	.399	.555	.694	.779	.821	.811	.755	.644	.520
2	.261	.427	.596	.733	.816	.860	.842	.774	.651	.520
3	.293	.466	.637	.775	.855	.896	.867	.786	.654	.524
4	.322	.500	.673	.815	.892	.928	.887	.789	.646	.512
5	.351	.538	.707	.846	.927	.955	.899	.790	.637	.496
6	.381	.567	.745	.886	.956	.973	.904	.784	.625	.476
7	.413	.605	.778	.917	.980	.985	.904	.773	.604	.456
8	.431	.638	.807	.937	.993	.987	.895	.751	.576	.429
9	.467	.664	.836	.957	1.000	.979	.874	.721	.546	.396
10	.496	.682	.842	.961	.999	.962	.845	.686	.510	.365
11	.511	.691	.847	.958	.965	.931	.806	.646	.474	.331
12	.517	.698	.849	.943	.953	.890	.763	.601	.433	.297
13	.529	.694	.830	.913	.917	.846	.717	.555	.394	.269

Figure 5

Correlation Array

It should be noted that the horizontal and vertical errors of the above table were calculated when the sampling density and incremental displacement were altered an equivalent amount. If the sampling density was 1 of 4 but the incremental displacement was kept at one unit, then the resulting correlation curve was no longer a smooth hill as expected, but a "rippled" hill which contained local peaks. Because the distance between these local maxima was equal to the distance between sampled elements from the image array, the phenomenon was similar to the "ringing" phenomenon encountered when working with sharp bandpass filters in the Fourier domain.

To demonstrate this observation a hypothetical one dimensional pattern and its associated template can be created. (See Figure 6.) Figure 7 illustrates the one-dimensional correlation array produced by 1 of 1, 1 of 3, and 1 of 4 sample densities respectively. Only the complete correlation calculation yields a smooth convex hill with a single peak. If, however, the 1 of 3 sample density is coupled with a 3i incremental displacement in the correlation array, then a smooth hill is produced, Figure 7 (d), and a satisfactory approximation of the best superposition can be made with a parabolic interpolation.

A one dimensional correlation was also calculated for the clavicle to determine the best vertical position of its centroid. The need for this information will be described further in conjunction with Program EXPANSION.

The correlation of the heart, however, provides some insight into a limitation of this correlation procedure which was not discussed above. The lung is a dark shadow surrounded predominantly by light areas. The

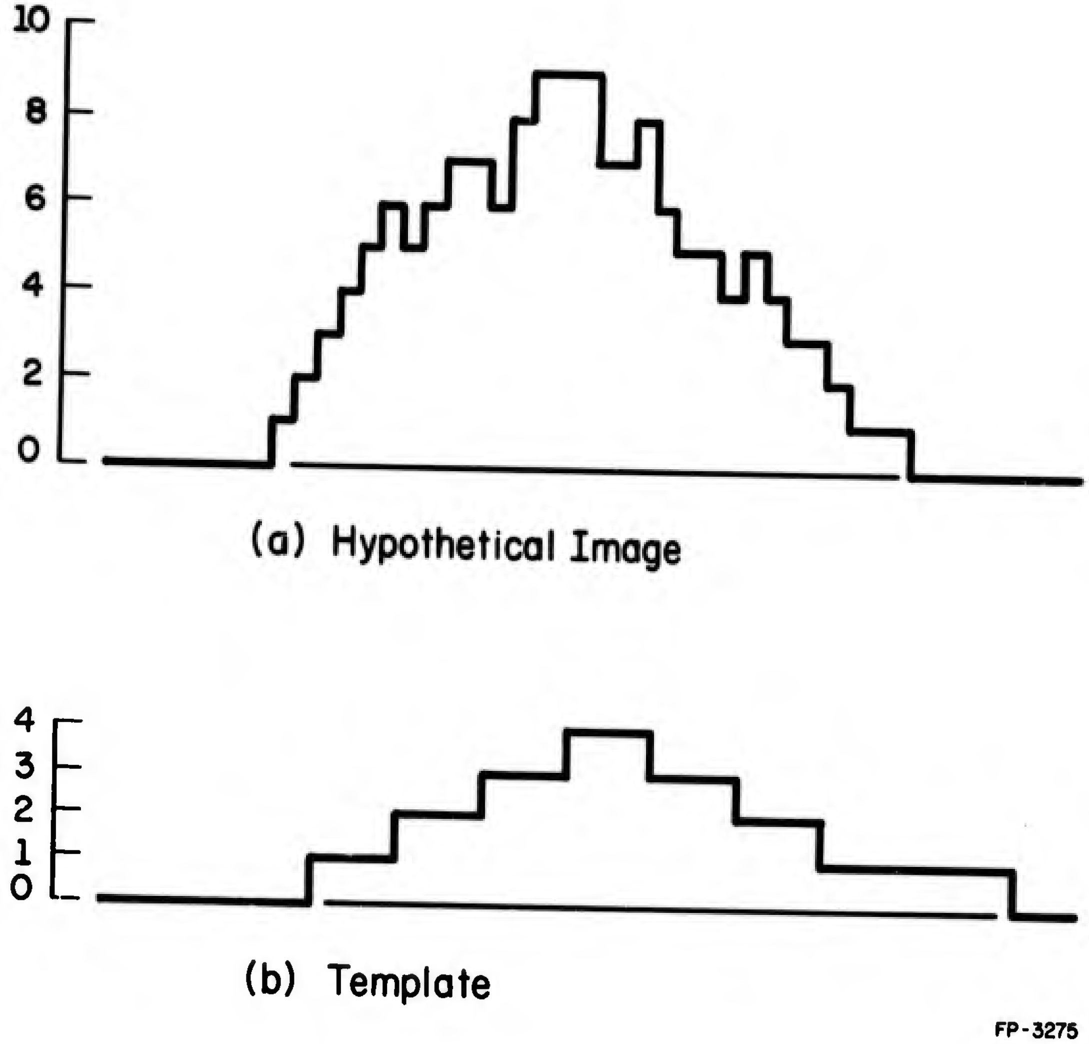


Figure 6

Hypothetical Image and Associated Template

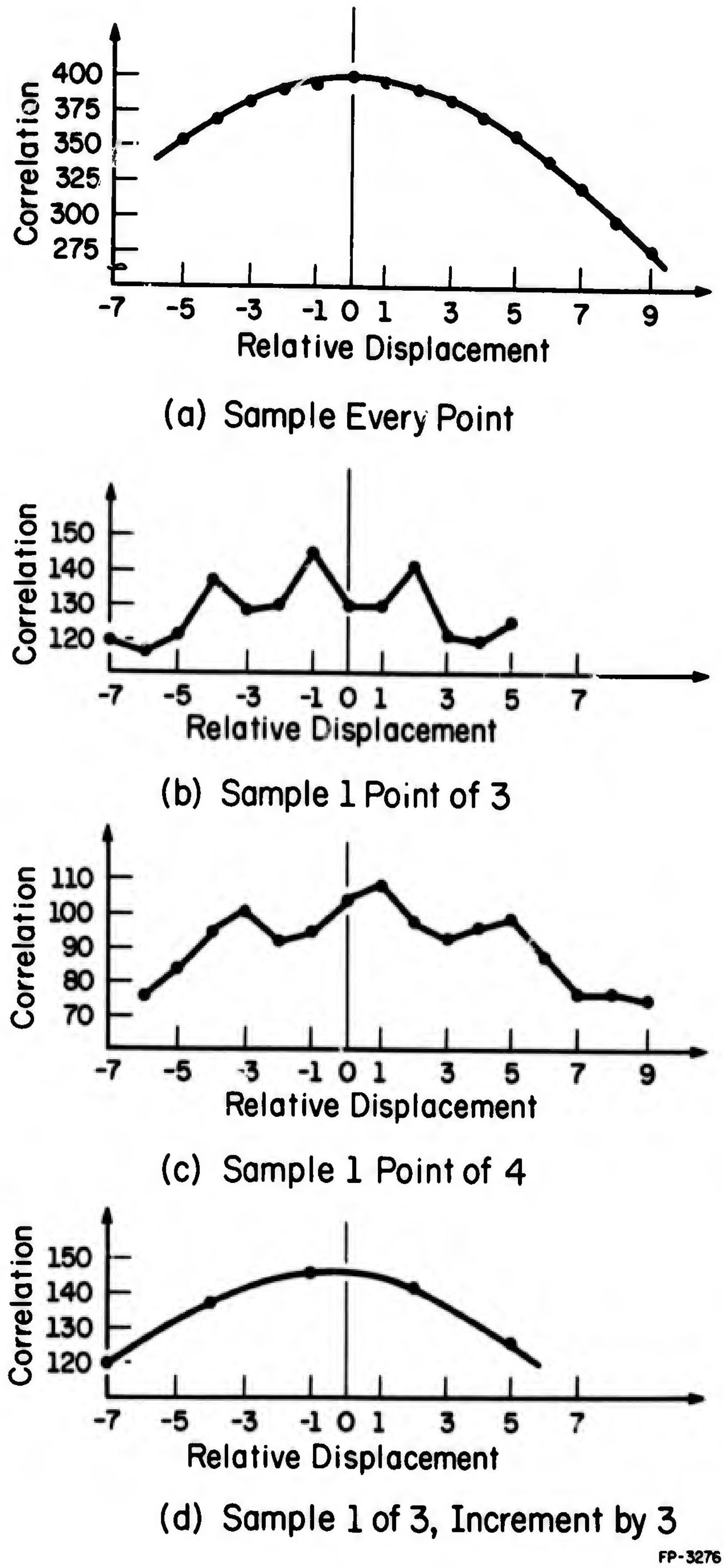


Figure 7

Correlation of One Dimensional Image

clavicle is light and surrounded by the dark lung. This leads to a correlation array which yields a maximum at the position of the best match between the template and the image array. The heart is a light area that is not bounded on the bottom. The result is that the correlation array no longer describes a smooth hill with a single peak at the best match. Since the abdominal region is lighter and larger than the heart, the correlation array exhibits a maximum which puts the centroid of the heart well into the region of the abdomen.

For this reason the correlation technique was not used to find the centroid of the heart. An alternative procedure was used. The horizontal and vertical "signatures" of the image array were taken after the manner of Hall.[4] The horizontal signature is created by forming a vector in which each element is the sum of the values of the elements in the corresponding row of the image array. Figure 8 illustrates the horizontal and vertical signatures. The centroid of the heart is calculated from the indicated features of the signatures.

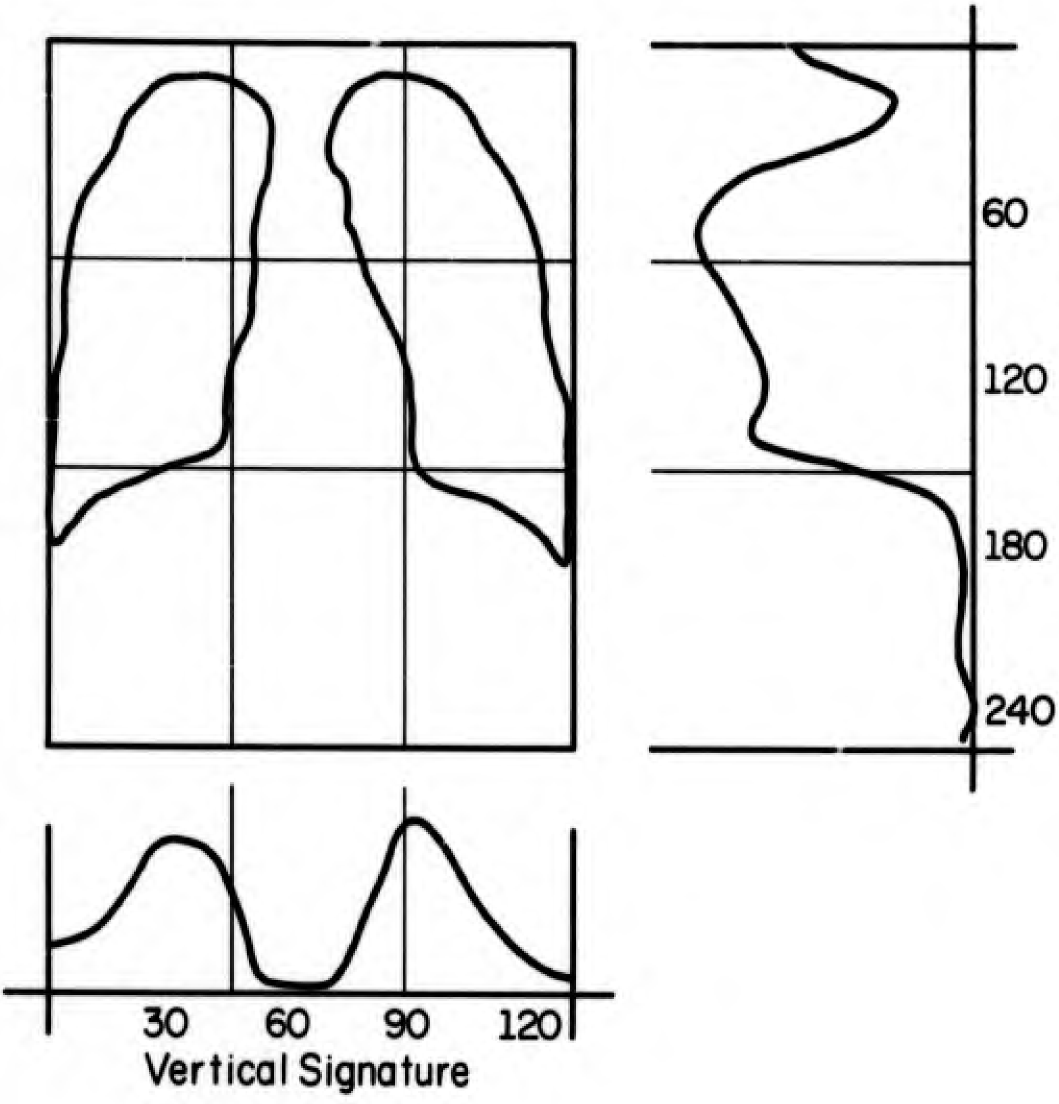


Figure 8

Signature of Image Array

4. GLOBAL OUTLINE PHASE

It was indicated above that local processing is not sufficient to reliably extract the edge of an organ. A global guide is needed to supervise a local search for the edge. There are two very important characteristics of chest X-rays which are useful in creating the global guide. First, the shape of the major organs (e.g., lung, heart, spine, claviculae, and abdominal region) is relatively fixed except in extremely pathological cases. Second, the relative position of the major organs is also fixed and reliable. This latter characteristic is used by Harlow in his region growing algorithm.[7] The fact that these characteristics do not change appreciably from one X-ray photograph to another means that prediction is possible. This line of reasoning was used in developing the following procedure.

A standard shape of the organ (we shall talk here about the right lung) was generated by statistically averaging the shape of a number of randomly selected lung images. (The outline of each of these samples was generated using human judgment.) Since the lung images are large dark masses surrounded predominantly by lighter areas, a gross outline of the lung can be created by a simple threshold operation performed on the image array. The standard outline can then be compared to the coarse outline of the test lung. It is to be expected that there will be lung variations in length and width. Therefore, to arrive at a best match between the standard outline and the coarse image of the test lung, "distortion" operations could be applied to the standard outline. The result of these operations would be to find a distorted standard outline which best conforms to the thresholded test lung image. This technique is made possible by the simple semantics of the class of pictures in that the standard outline is implicitly a syntactic device. The distortion operations may change the size and proportions of the standard outline but they do not change the basic shape in any essential way.

The thresholding operation is accomplished quite simply due to the fact that the test X-rays used in this investigation exhibited a reliable distribution of light intensities. The heart, spine, and abdominal regions consistently had light intensity values of zero (the brightest) and the central portion of the lungs averaged between 12 and 15. (The value of 15 represents the darkest quantized light value.) A fixed threshold value was sufficient to reliably yield an approximate or coarse outline of the lung image. A coarse heart outline was obtained in a similar manner. In this case, however, the heart was surrounded on three sides by dark areas of the two lungs. The thresholded image had to be "reversed" (zero converted to one and one to zero) in the case of the heart. An additional difficulty occurred because the lower edge of the heart is not apparent in the X-ray image. The regions of the heart and abdomen have almost identical photographic densities so that a thresholding operation cannot distinguish between them. In order for Program EXPANSION to work, the organ under consideration must be bounded on all four sides so that there is no direction in which the distorted standard outline can be expanded without limit. This problem was solved by taking a vertical "signature" of the image array as described above. Figure 8 shows how the vertical signature clearly indicates the approximate position of the lower edges of the two lungs; this position can also be used as the boundary of the lower portion of the heart. To constrain the expansion of the distorted heart outline, the row of the image array indicating the lower limit of the lungs was used as a limit to the expansion of the heart outline. This was achieved by artificially setting to zero all elements of the thresholded image below this row. Figures 9 and 10 show the final thresholded images of the right lung and heart respectively. Picture elements containing a value greater than the threshold are represented by "0", those below by a blank.

Figure 11 is a flow-chart of Program EXPANSION. The standard outline of the organ (here, the right lung) is superimposed over the test organ using the center determined earlier from the correlation calculations. A measure of the degree of match between the two is calculated and stored. This measure is calculated as follows. First, the array elements which are surrounded by the distorted standard outline and are "1" are counted. Then the elements surrounded by the outline which are "0" are counted. The measure of match between the distorted standard outline and the thresholded lung image is the difference between the number of "1"s and the number of "0"s. This measure is used as a figure of merit of match between the thresholded lung image and the distorted standard outline. The purpose of the program is to apply the distortion operations iteratively to the standard outline.

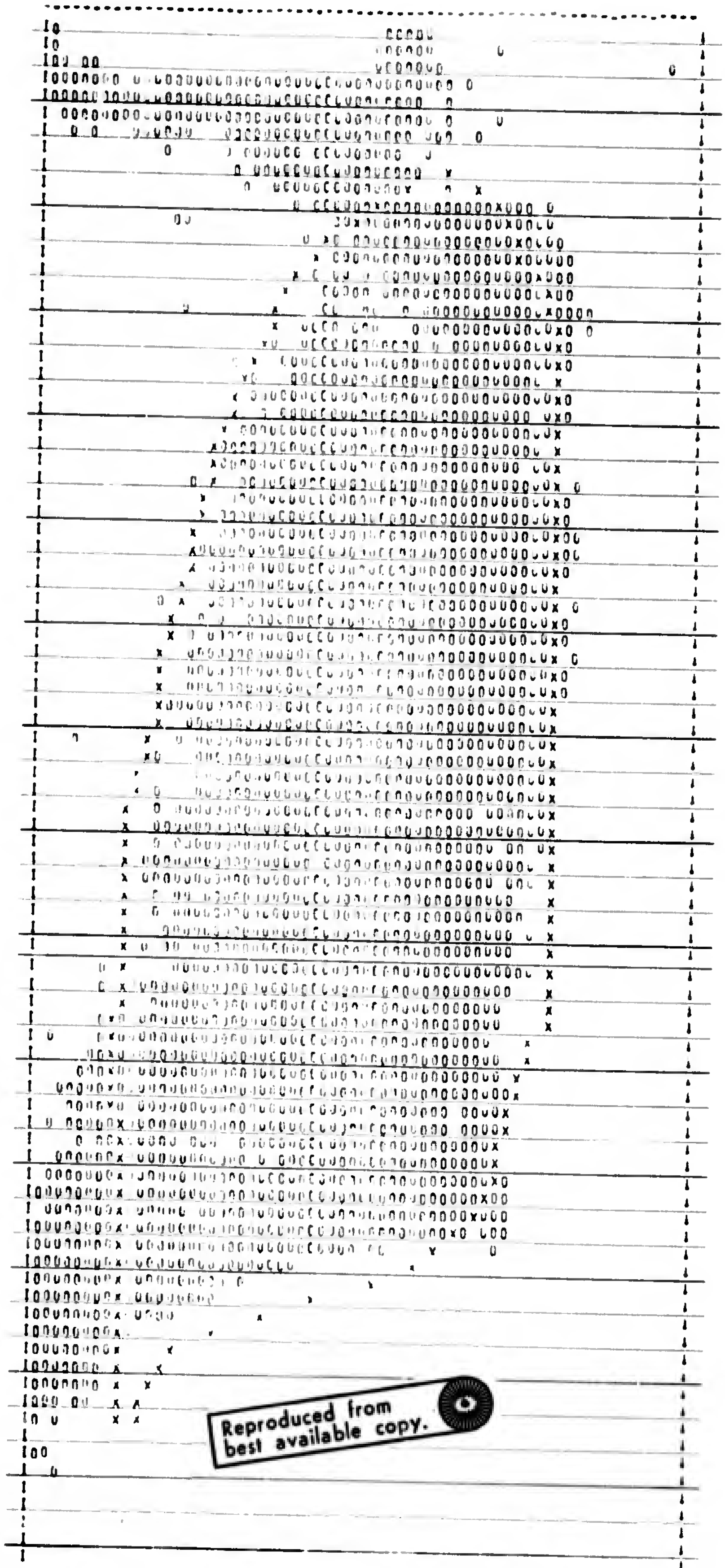


Figure 9

Thresholded Lung and Outline

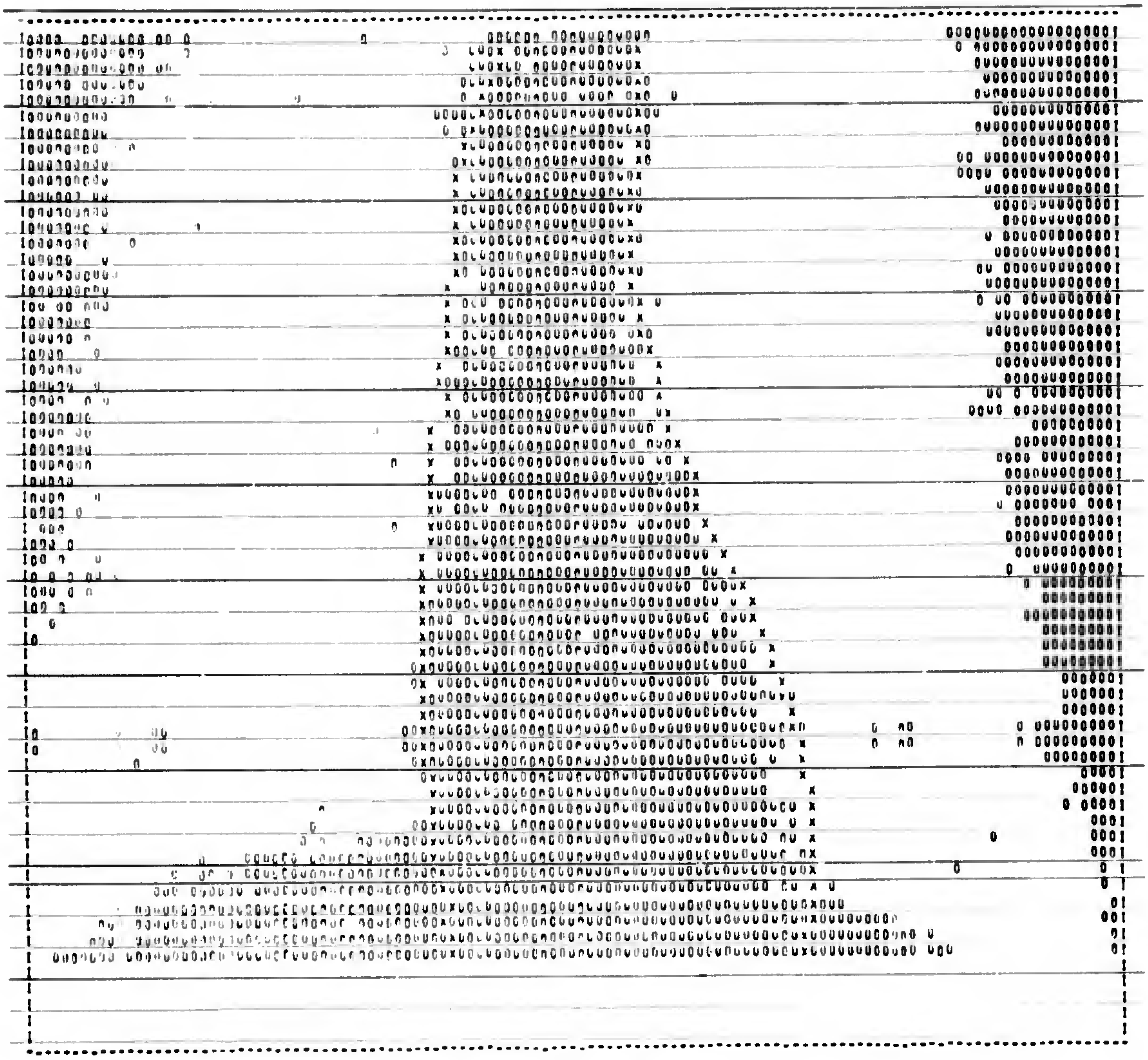


Figure 10

Thresholded Heart and Outline

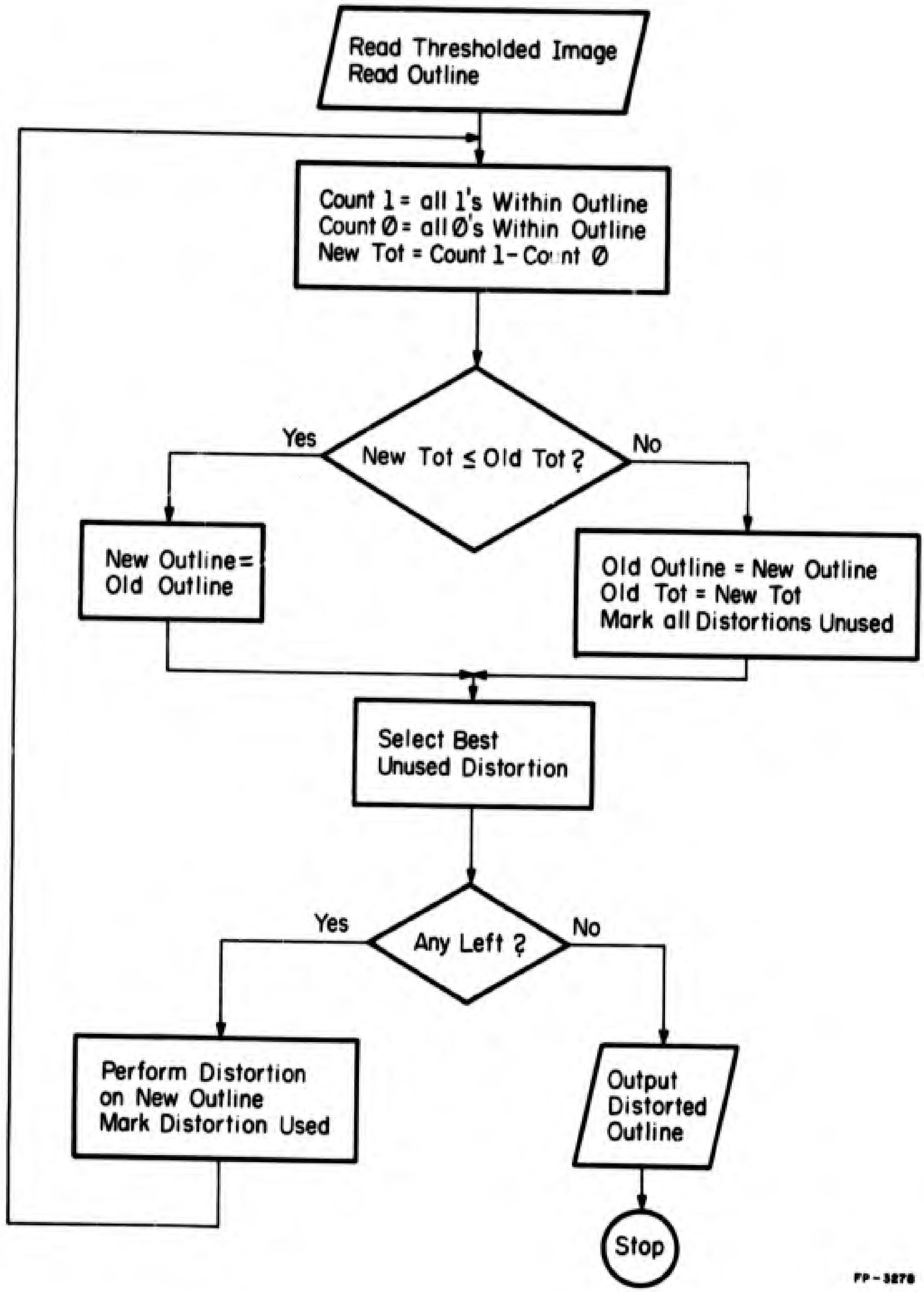


Figure 11

Program EXPANSION

The following list contains the distortion operations which were applied to the standard outline of the lung:

a) Vertical Expansion
b) Horizontal Expansion
c) Vertical Shrinking
d) Horizontal Shrinking
e) Vertical Translation
f) Horizontal Translation
g) Clockwise Skewing

These same distortion operations were used on the standard outline of the heart with the exception that the skewing distortion was replaced by two new operations. These were expansion and shrinking of the outline in the horizontal direction. The operations differ from b and c above in that the rate of expansion became progressively greater from the top of the heart outline to the base. It was felt that these operations were sufficient to account for the major variations of the lungs and heart normally encountered.

If the figure of merit of match is greater than it was before the operation, then the new distorted standard image is retained and the next successive distortion operation is applied to this distorted standard image. If the figure of merit is smaller than before, the result of that distortion operation is erased and a different distortion operation can increase the figure of merit of match between the distorted standard image and the thresholded organ image. Figures 9 and 10 give examples of the comparison between the test image and the final distorted standard outline for the right lung and the heart. In these figures the location of the distorted outline is represented by "X."

In order to reduce the running time of Program EXPANSION two sets of heuristics were created to predict the distortion operation which would be the most effective in increasing the figure of merit. The first heuristic would sense for the presence of the thresholded lung image at the location of the distorted standard outline. The presence or absence of the lung image along segments of the outline could be used to calculate the distortion operation which would be the most effective to increase the match. The second heuristic was to simply re-apply the most recent, successful distortion operation. If unsuccessful, it would apply the second most recently used operation, etc.

Unfortunately, neither heuristic seemed to increase the efficiency of Program EXPANSION very much. In fact the second heuristic appeared to increase the running time over a random selection of distortion operations. It was worse than no heuristic at all. Further work is needed to develop an effective heuristic which is computationally simple.

The technique used in Program EXPANSION is sometimes referred to as "hill climbing" (because of its search for a maximum figure of merit of match) and is subject to the problems associated with hill climbing algorithms. If the "hill" contains local maxima, then the algorithm may find a local peak and halt. This problem was not encountered in the application of Program EXPANSION to the three sample X-rays. EXPANSION can also be viewed as a tree searching algorithm. The original standard outline can be considered a root of a tree and each distorted standard outline obtained from it is a node in this tree. The object of the program is to search the tree to find the node with the largest figure of merit.[9]

At the termination of this procedure a smoothing algorithm was applied to the distorted standard outline to insure that there were no sharp edges or discontinuities. This was done because Program EDGE uses the slope of the distorted standard outline as an important global guide. A sharp change in slope or a discontinuity of the outline would create inconsistencies in its operations.

5. LOCAL DETECTION PHASE

The above procedure will yield an approximate outline of the lung or heart. To determine the edge of the organ more precisely, however, requires that additional calculations be performed on local information contained in the original image array. Two characteristics of the distorted standard outline provided by Program EXPANSION can now be used as a form of global or semantic guidance. First, each point of the distorted outline is located near the edge of the organ, therefore local processing can safely be confined to the neighborhood of the outline. Second, the slope of a small segment of the distorted outline should be nearly equal to the slope of the edge of the organ in that neighborhood. (See Figures 9 and 10.) This second property is useful in the following procedure.

The most rapid rate of change of light intensity is along a path which is perpendicular to the edge of the organ. (Again we will use the right lung as the example of these principles.) "Noise" such as rib edges, which might be misleading are, in general, not parallel to the lung edge. Therefore a smoothing operation in a direction parallel to the distorted standard outline will tend to "blur" extraneous edges without effecting the lung edge. This smoothing operation is made feasible because the edges of the lungs and heart are gently curving lines relative to the local search except at a few points (e.g. the tips of the lungs.)

Figure 12 is a general flow diagram of Program EDGE. The first function of EDGE is to select points along the perimeter of the distorted standard outline which are approximately equally spaced. The spacing used

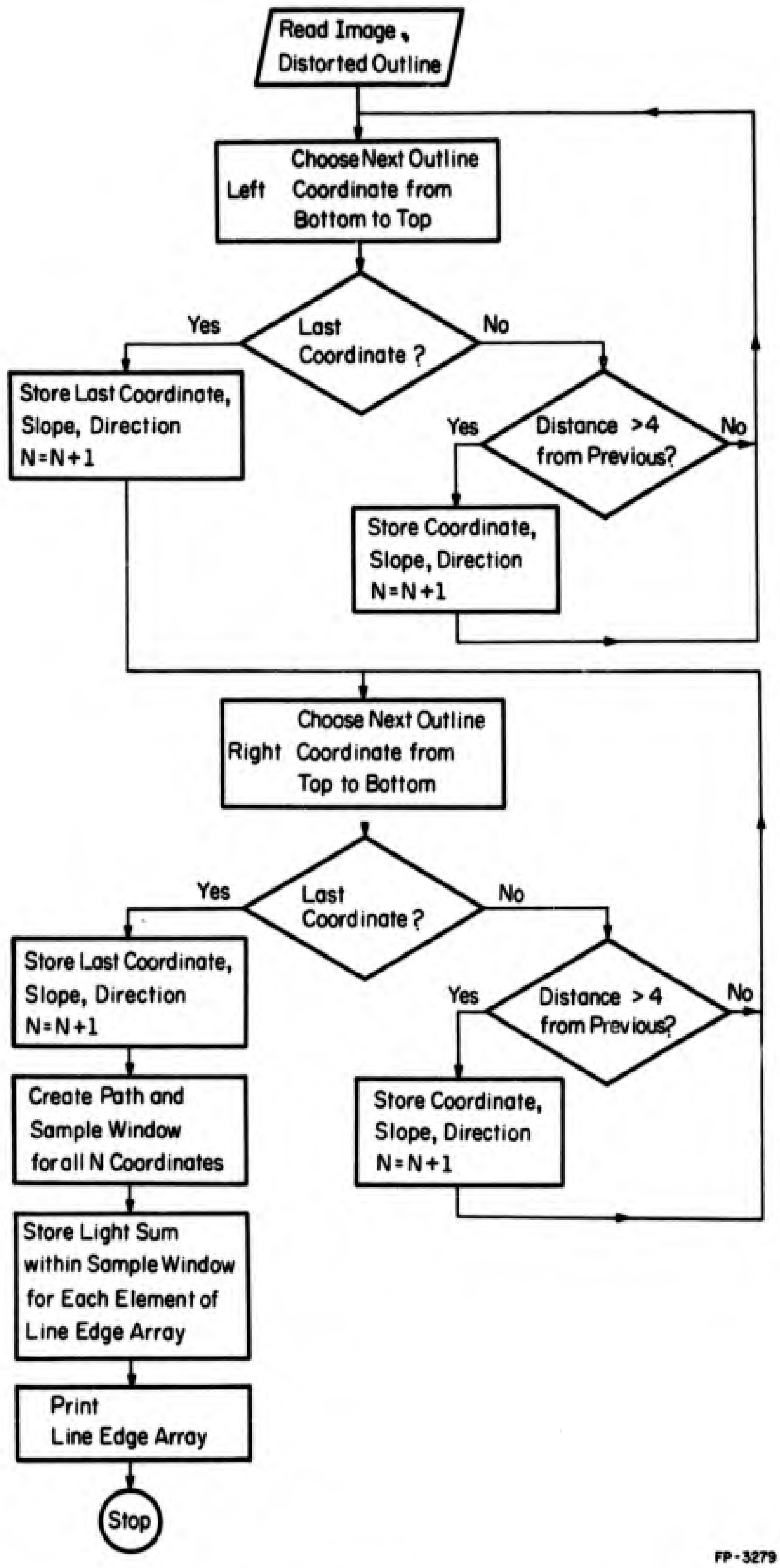
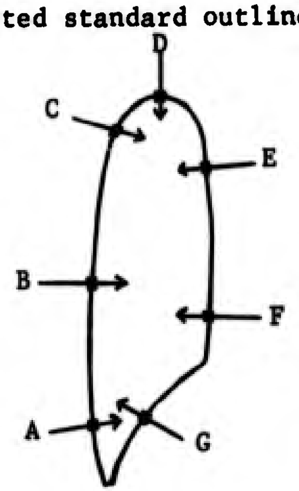


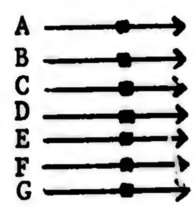
Figure 12

Program EDGE

in the following diagrams is about seven to eight picture elements, and is adjustable to allow for varying degrees of detail. The slope of the outline at these points is calculated. For each selected point a path is created which is perpendicular to the slope of the outline at that point. This is best visualized if one imagines the distorted outline as it appears in the image array. The path mentioned above is an ordered sequence of coordinates of elements in the image array whose slope is approximately perpendicular to the slope of the distorted outline where they intersect. The figure below illustrates the relationship of the paths to the distorted standard outline.



Relationship of Paths
to Distorted Outline



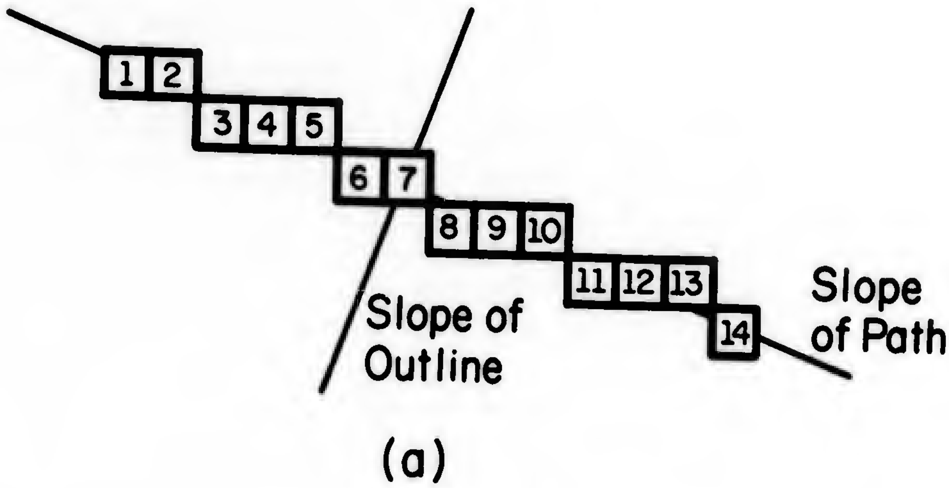
Formation of Line
Edge Array

The first path is created at the lower tip, and successive paths are provided in a clockwise sequence along the perimeter. The first coordinate pair of the path always refers to a region outside the outline (and lung edge). The arrows indicate the importance of direction. Two new arrays are formed. A coordinate array D_{mn} is created to store the coordinates of the ordered sequence of elements which form each path. The second array, the line edge array L_{mn}, will store in each element L_{ij} the summed light intensity measured in a region of the image array pointed to by the coordinate pair D_{ij} of the corresponding element of the coordinate array.

Each path is 25 picture elements long, and contains the intersection point of the distorted standard outline at the 15^{th} element of the path. This allows margin to insure that it will intersect with the real edge of the lung. Figure 13 illustrates how this is accomplished. First the slope of the path is calculated, then the sequence of picture elements which most nearly approximates an ideal (smooth) path with this slope is created. The result, as illustrated in Figure 13 (a), is a discrete approximation of an ideal path.

The smoothing operation is accomplished by creating a "sample window" perpendicular to the slope of the path. (See Figure 13 (b).) At each coordinate pair of the path the light intensities within the sample window are summed. The value of the sum is then entered into the corresponding element of the line edge array. Each path consists of 25 positionings of the sample window and each row of the line edge array contains the summed light value at each position of the sample window. Figure 14 illustrates a typical line edge array.

The line edge array illustrated in Figure 14 has some interesting semantic properties which aid in the final extraction of the edge of the organ. First, the left-hand portion of the array contains summed light values sampled in a region which is <u>external</u> to the organ; the right-hand



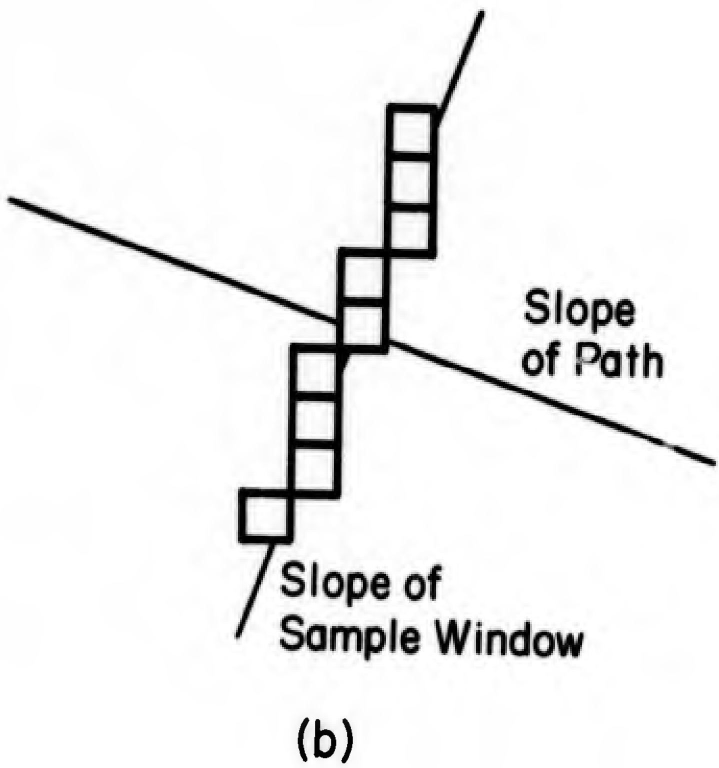


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Figure 13

Construction of Path and Sample Window

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	COLUMN	STATUS
0	0	0	0	0	0	0	28	81	58	67	77	63	86	74	65	49	34	34	24	8	3	6	0	0	8	REJECT
0	0	0	0	0	0	0	38	84	80	83	91	78	83	67	52	29	25	54	44	21	9	6	2	5	18	OK
0	0	0	0	0	0	1	48	81	99	86	90	81	61	57	42	37	48	54	68	52	50	24	19	11	17	OK
0	0	0	0	0	0	1	78	50	95	90	69	67	46	46	45	61	62	78	63	75	84	74	51	40	15	OK
0	0	0	0	1	0	0	69	55	86	87	48	46	35	61	72	75	84	73	72	82	82	72	80	82	14	OK
0	0	0	0	2	0	0	66	75	58	58	34	31	34	61	70	87	82	86	81	73	74	74	81	74	13	OK
0	0	0	0	0	0	1	63	50	43	44	28	20	21	45	69	79	67	61	59	41	57	56	68	52	13	OK
0	0	0	0	0	0	0	7	30	29	27	17	15	5	10	15	27	45	39	44	59	47	46	52	65	14	OK
0	0	0	0	0	0	0	3	18	13	19	6	3	3	4	15	11	17	24	31	42	47	37	48	44	15	OK
0	0	0	0	0	0	0	0	7	6	7	7	0	1	0	5	12	16	23	21	25	30	28	39	41	16	OK
0	0	0	0	0	0	0	5	8	2	1	0	3	0	3	6	10	22	20	14	13	20	35	43	48	16	OK
0	0	0	0	0	0	0	1	4	3	2	5	0	0	0	3	2	21	20	35	34	30	42	38	46	18	OK
0	0	0	0	0	0	0	0	1	6	2	7	1	5	1	4	10	12	19	29	22	43	46	34	47	16	OK
0	0	0	0	0	0	0	0	1	0	8	6	1	0	0	4	15	13	17	92	13	30	25	36	47	16	OK
0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	12	15	21	24	30	30	40	40	54	16	OK
0	4	0	0	0	1	0	0	0	0	0	0	2	0	0	2	9	15	21	20	29	29	74	71	66	17	OK
1	0	0	0	0	1	0	0	0	0	0	0	3	1	4	21	32	46	50	40	60	48	76	75	63	15	OK
0	0	0	0	0	0	0	0	0	1	0	4	3	2	6	14	29	35	35	47	61	62	66	84	75	15	OK
0	0	0	0	0	0	0	0	1	0	0	3	5	11	16	17	17	25	33	46	47	63	71	75	63	13	OK
0	0	0	0	0	0	0	0	1	2	0	0	0	9	12	18	23	30	39	46	47	43	49	51	48	14	OK
0	4	0	0	2	0	0	1	0	1	0	0	3	11	14	37	37	41	43	47	59	57	65	71	74	14	OK
0	4	0	1	0	0	0	1	1	3	2	1	6	5	7	12	13	29	28	47	52	64	72	89	84	13	OK
0	0	0	1	0	0	0	0	0	1	0	1	4	7	8	14	18	23	28	37	38	46	59	62	75	13	OK
0	0	0	0	0	0	0	0	0	0	1	3	10	10	16	16	27	28	36	56	52	54	57	64	51	13	OK
0	0	0	0	0	0	0	0	0	1	0	7	12	9	10	16	15	21	34	47	42	45	66	58	58	12	OK
0	0	2	0	0	0	0	2	0	2	2	8	4	13	18	12	14	19	27	33	26	52	54	47	43	12	OK
0	0	0	0	0	0	2	0	1	1	1	3	6	15	18	15	25	32	29	23	27	43	35	43	33	13	OK
0	0	0	0	0	0	0	0	0	0	1	2	3	11	8	10	22	19	21	24	31	32	33	34	33	14	OK
2	3	2	2	3	1	1	3	2	4	6	8	8	12	14	13	16	17	18	20	24	26	28	31	34	10	OK
1	6	2	0	7	13	11	4	12	7	8	19	25	23	27	22	18	28	39	52	46	54	48	32	32	6	OK
2	3	5	10	10	12	13	14	14	13	11	11	10	14	16	20	26	30	27	33	32	23	20	16	8	13	OK
0	0	0	0	0	0	0	0	1	1	2	0	2	8	16	25	35	44	43	46	45	40	34	32	30	14	OK
0	0	1	0	1	0	0	0	4	0	0	0	0	5	5	5	15	21	36	45	54	59	51	40	28	14	OK
0	0	0	0	0	0	0	0	1	0	0	0	4	6	16	5	23	26	30	35	42	44	37	27	23	13	OK
0	0	0	0	0	0	0	0	0	0	0	0	9	10	13	12	20	21	20	32	37	35	35	31	33	13	OK
0	0	0	0	0	2	0	0	0	0	0	0	9	9	10	11	33	29	33	33	32	29	26	30	26	13	OK
0	1	0	0	0	2	0	0	0	2	1	0	10	9	12	15	22	26	25	19	24	23	25	26	16	13	OK
2	3	0	0	0	2	0	0	0	0	7	1	9	6	10	14	15	23	21	31	32	34	31	40	39	13	OK
1	0	0	0	0	0	0	0	2	0	0	1	5	6	9	17	25	29	31	28	46	50	58	57	70	13	OK
1	0	0	0	0	0	0	0	4	0	0	0	4	10	16	27	33	36	42	54	59	62	71	71	78	13	OK
1	0	0	0	0	0	0	1	0	1	0	0	2	5	18	29	35	45	52	61	56	66	71	86	66	14	OK
0	0	0	0	0	0	0	2	1	1	0	0	0	5	23	35	39	46	63	57	55	55	70	81	61	14	OK
2	0	0	0	0	0	0	0	1	0	0	0	0	4	21	28	36	42	48	51	44	43	67	85	78	14	OK
0	0	0	0	0	0	0	0	0	0	0	0	0	1	23	37	43	43	56	57	58	52	69	82	78	15	OK
0	0	0	0	0	0	0	0	0	0	0	0	1	0	19	30	41	42	41	41	40	29	56	64	73	15	OK
0	0	0	0	1	0	0	0	0	1	0	0	1	1	14	20	25	29	33	35	24	33	39	40	49	15	OK
0	0	1	0	0	0	0	1	0	1	0	2	1	6	11	22	33	43	37	37	29	42	37	31	36	14	OK
0	0	4	0	0	0	0	1	0	0	0	0	1	5	13	23	62	37	27	24	23	33	23	20	41	14	OK
0	0	0	0	0	0	0	0	0	0	0	0	0	4	17	15	58	31	43	20	20	18	19	29	47	14	OK
0	0	0	0	0	0	0	0	0	0	0	0	0	4	20	15	28	37	33	33	36	37	28	39	39	14	OK
0	0	0	0	0	0	0	0	0	0	0	0	0	6	12	21	31	35	32	28	34	37	33	33	37	14	OK
0	0	0	0	0	0	0	0	0	1	0	5	0	9	15	23	40	41	50	51	50	58	49	45	47	14	OK
0	2	0	0	0	0	0	0	7	4	0	2	0	2	7	15	33	45	52	57	59	54	56	61	54	15	OK
0	2	0	0	0	0	0	0	7	1	0	1	0	2	2	12	24	42	44	48	43	44	33	43	51	18	OK
0	0	0	0	0	0	0	0	0	0	0	2	0	1	10	12	29	42	44	51	53	48	37	47	37	15	OK
0	0	0	0	0	0	0	0	5	0	0	2	1	4	10	16	26	41	51	52	58	56	59	69	49	14	OK
0	0	0	0	0	3	0	0	0	0	5	0	0	1	3	8	20	28	44	51	50	48	64	69	59	16	OK
0	0	0	0	0	0	0	0	1	0	0	2	4	16	32	42	45	47	57	44	59	71	57	55	62	13	OK
0	0	0	0	0	0	1	0	3	0	3	6	18	34	50	57	57	57	56	63	66	71	65	65	61	12	OK
0	0	0	0	0	1	2	1	0	2	5	7	19	33	56	55	67	60	66	60	72	68	61	54	55	11	OK
0	1	0	0	2	0	0	1	0	0	1	7	8	19	36	63	76	79	86	70	80	61	60	51	67	12	OK
0	0	0	0	1	0	0	0	0	0	1	2	1	4	16	42	46	71	80	62	77	79	61	66	70	14	OK
0	0	0	0	0	0	0	2	0	0	2	8	5	7	8	21	32	58	67	83	78	84	76	79	73	12	OK
0	0	0	0	0	0	1	0	0	0	0	0	5	2	6	13	14	26	47	73	81	77	71	73	67	15	OK
0	0	0	0	0	0	0	0	0	0	0	0	1	0	4	5	11	24	38	77	72	70	55	63	54	15	OK
0	0	0	0	0	0	0	1	1	0	2	0	6	6	13	28	43	45	54	54	55	63	62	71	63	13	OK
0	0	0	0	0	0	1	0	1	4	3	10	28	27	39	44	46	66	74	78	76	80	89	69	48	12	OK
0	0	0	1	0	0	0	1	5	2	7	23	35	46	55	78	68	82	61	81	67	58	76	16	0	11	OK

Figure 14

Line Edge Array

portion contains values sampled in a region internal to the organ. One element in each row contains the summed light intensity when the sample window was approximately superimposed over the edge of the lung. Second, if the position of the edge of the organ were labeled for each row in this array, the sequence of labeled points would appear as a wavering vertical line. Third, this vertical line should have very few discontinuities. (That is, the distance between any two line segments should be less then four picture elements in all but a very few instances due to the gentle curve of the organ edge.)

It was mentioned above that the boundaries of the lung and heart might be detected by searching for large differences of light intensity of adjacent picture elements. This technique was considered for finding the edge in the line edge array but the results were very unsatisfactory. This was because the differences of summed light intensity in a region well within the lung were frequently much greater than the difference at the actual lung edge. A normalized difference of intensity of the form:

$$(I_{jk} - I_{j-1k})/I_{jk} \tag{3}$$

was considered where I_{jk} is the value of the j^{th} element of the k^{th} row of the line edge array. This procedure is very effective at identifying the edge but is also sensitive to noise for small light values. Figure 15 shows graphically the summed light values contained in sequential elements of typical rows from the line edge array. The location of the intersection with the lung edge is indicated on the graph. It is clear that a variety of contours must be expected. In particular Figure 15(d) shows the contour of a path which passes through a dark image adjacent to the lung. The

Figure 15

Typical Contours of Summed Light Intensity edge of the lung in this instance is the valley between this dark image and lung. In this case a search for a local light intensity minimum would be helpful. The variety of shapes encountered as demonstrated in Figure 15 contributes to the problem of finding one simple, universal calculation which will reliably detect the edge of the lung in all instances.

Unable to find one completely effective procedure for detecting the lung edge, Program DETECT was written to use two types of procedures. (See Figure 16 for flow-diagram of Program DETECT.) First a simple threshold test is performed on each row beginning from the right. This has the effect of testing summed light values obtained from a region internal to the organ first, then testing values nearer the edge. The column location immediately to the right of the first element containing a value lower than the threshold (in this case 4) is marked. This is done for each row of the line edge array. The second step of Program DETECT is to search for discontinuities. If none exists, then the column locations marked previously are assumed to map (via the coordinate array) to the edge of the lung. If discontinuities exist, then the program searches for local minimal which might resolve the discontinuity. If no minimum value is found which will do this, then that row is not used to identify the lung edge. (The STATUS column in Figure 14 is labeled with REJECT.) The program halts when it cannot avoid existing discontinuities.

Detection of the heart edge by Program EDGE is much more direct. This is possible because the heart edge is not obscured by rib edges or misleading shadows as is the lung edge. A thresholding operation as described above is adequate to identify the edge in this case.

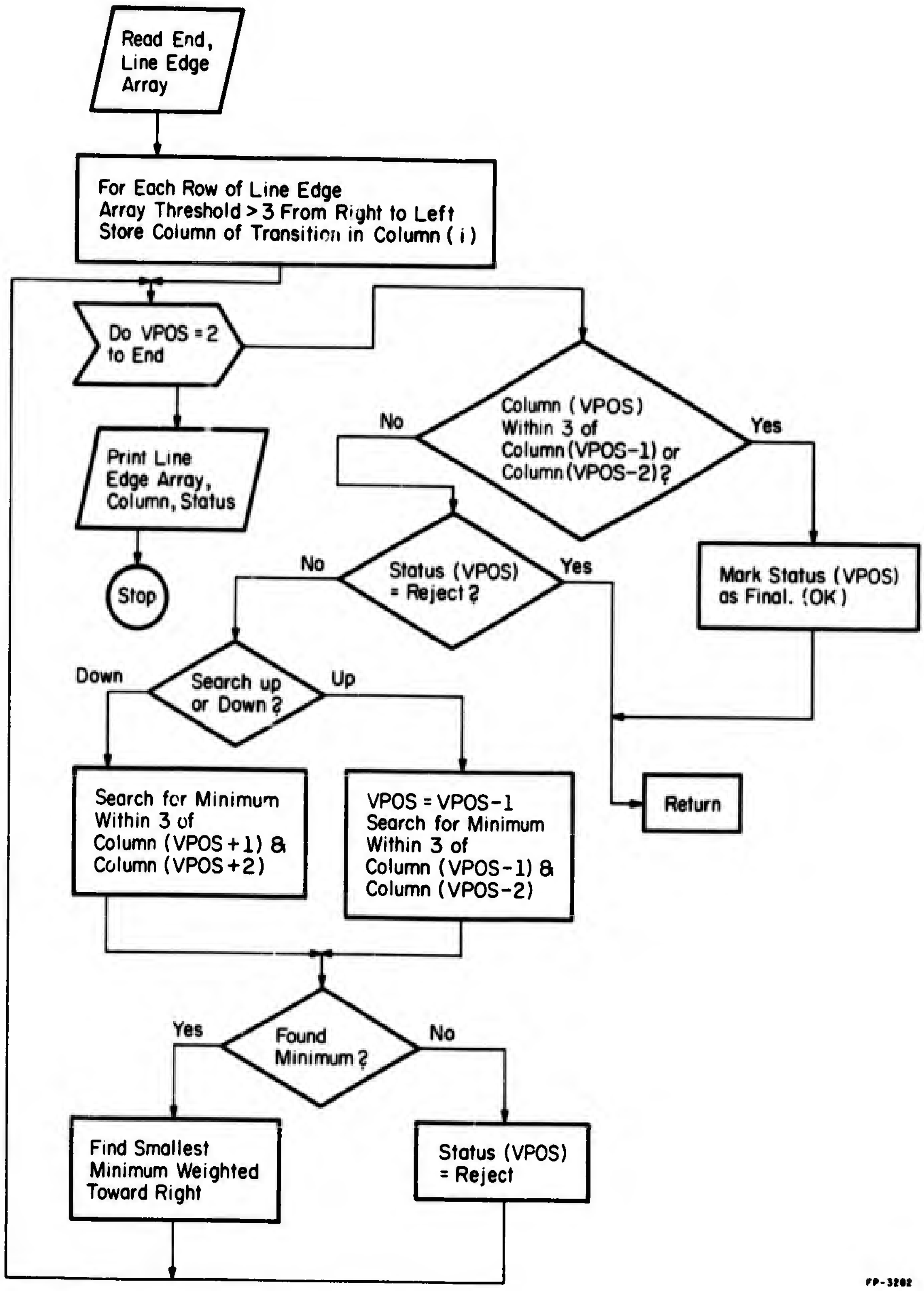

Figure 16

Program DETECT

The results of Program DETECT are displayed in Figure 14. Since each array element of Figure 14 has an image array coordinate associated with it, the detected sequence of points in Figure 14 maps to a sequence of points in the image array. When these points are joined by a linear interpolation algorithm, the result is the edge of the organ. Figures 17 and 18 illustrate the results of the search for the edges of the right lung and heart on three sample chest X-rays.

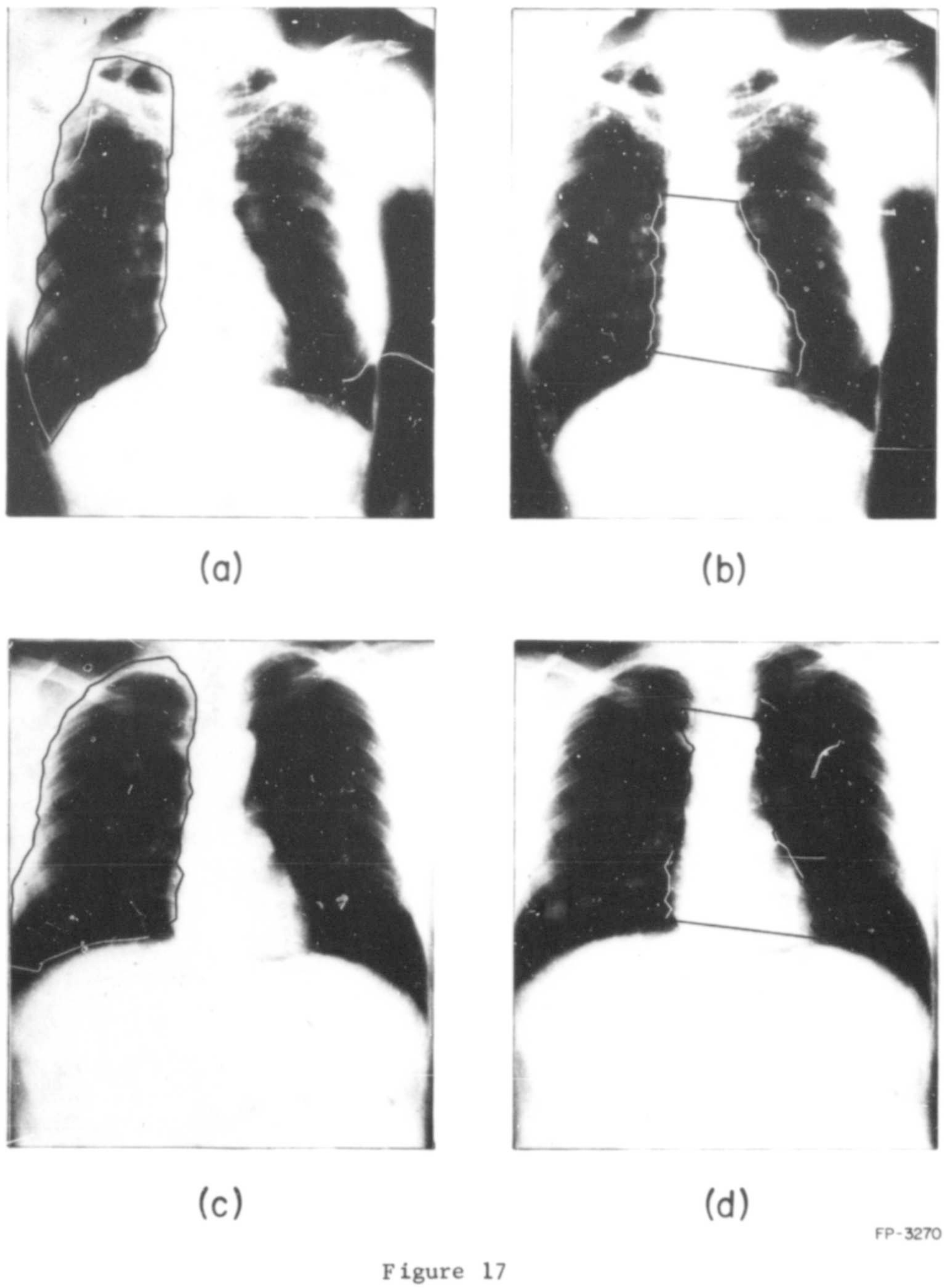

Figure 17

Lung and Heart Outlines of Test X-Rays

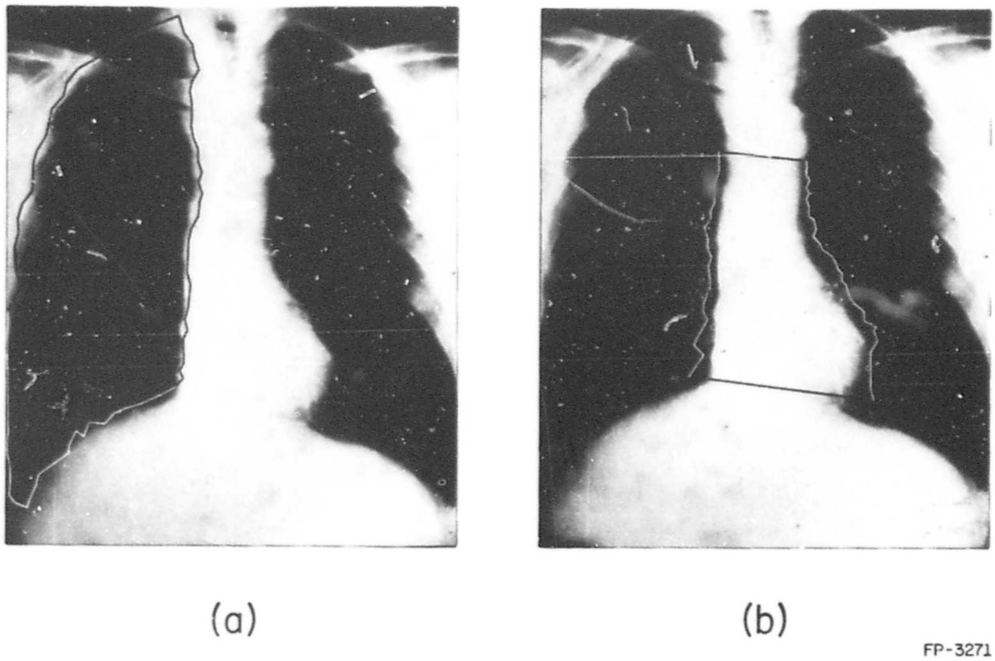

Figure 18

Lung and Heart Outlines of Test X-Rays

6. CONCLUSION

Figures 17 and 18 clearly indicate the abilities of this system. This technique is sensitive to very faint edges as the outlines of the lungs demonstrate. It should be noted however that identification of the top of the lungs still presents a formidable task. The intricacy of the bone structures there made detecting the real edge very difficult. Figure 17(c) indicates an instance where an erroneous edge was selected.

One of the design considerations of the system was to try to minimize the amount of computation needed to solve the problem. The degree to which this objective was achieved is questionable. The correlation function computation was adequately limited by sampling data points. Each correlation computation for the lung consisted of summing 150 multiplied pairs. A hill climbing program to find the maximum correlation value would be very efficient. If the photo-scanning device incorporated a coherent light source, the correlation could be performed in the Fourier domain in the fraction of a millisecond.

Program EXPANSION however was computationally difficult for a sequential computer. If the program were implemented on a parallel machine such as the ILLIAC III, then comparisons between the standard outline and the thresholded image would be performed much more rapidly. It also ran slow because the heuristic techniques for selecting the next distortion operation were poor. More thought into selection of these selection parameters would improve running time considerably. Programs EDGE and DETECT executed very fast.

It is possible that processing time could have been reduced if the "signature" technique (used for locating the centroid of the heart) had been applied to finding the centroid and size parameters of the heart and lungs. An iterative procedure as described by Hall[4] might have been sufficient to extract the information needed to perform a distortion of the standard outlines. This would have eliminated the need for Programs CORRELATION and EXPANSION. Using the signature technique to make size and shape measurements would restrict the generality of this approach.

Another question can be raised about the diversity of the techniques used. It is difficult to know when specialized procedures are essential to achieve proper problem solution, and when they are used only because much more powerful methods have not been developed.

One very strong limitation of the system configuration of Figure 1 was that the programs used in picture analysis did not have access to the original photograph. The exclusive representation of the image was the image array. The system configuration shown in Figure 19 would be more desirable for several reasons. First, a single image array would not need to be stored in the computer. Instead specialized images could be requested on demand by the operating program. This would allow a rapid scan by the optical scanning device when only coarse, global information is needed by the program. However, when greater detail is necessary for local processing of a small patch of the entire image, then the optical scanner could be commanded to deliver exactly that type of information.

Second, chest X-ray photographic film exhibits very large grey scale range. A fixed light quantizer yields a poor representation of the

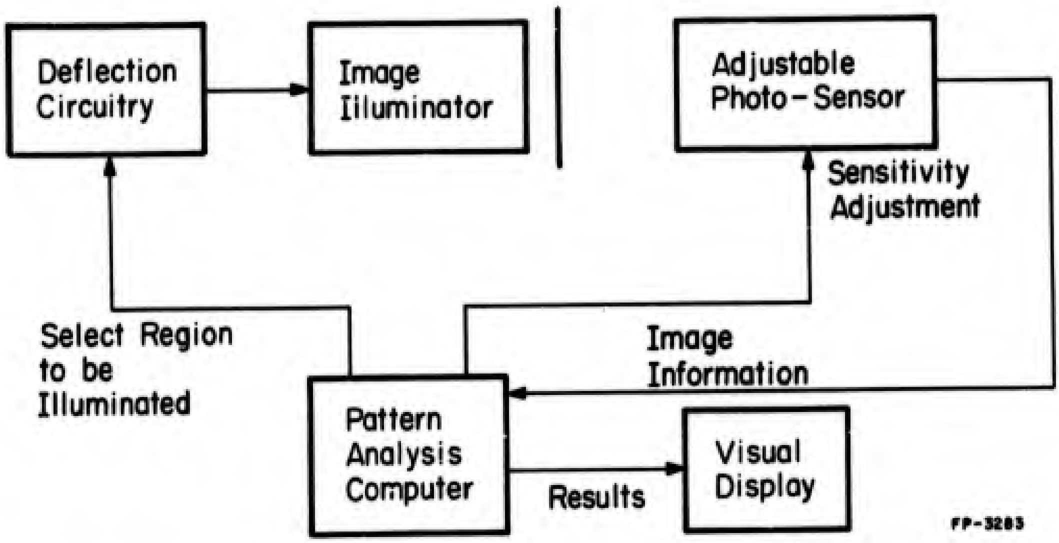

Figure 19

Hypothetical System

original image. Figure 20 illustrates this point by showing the distribution of quantized light levels in a typical photograph. More than half of the total number of image elements contained the value zero. Unfortunately the equipment used in this research did not allow any flexibility in the quantization process and does not currently allow quantization to a finer grey scale. The latter would have made possible the enhancement technique of Distribution Linearization discussed by Hall.[5,6] A more flexible photosensor could possibly be used in this manner to yield an image representation richer in detail making the feature extraction phase less difficult.

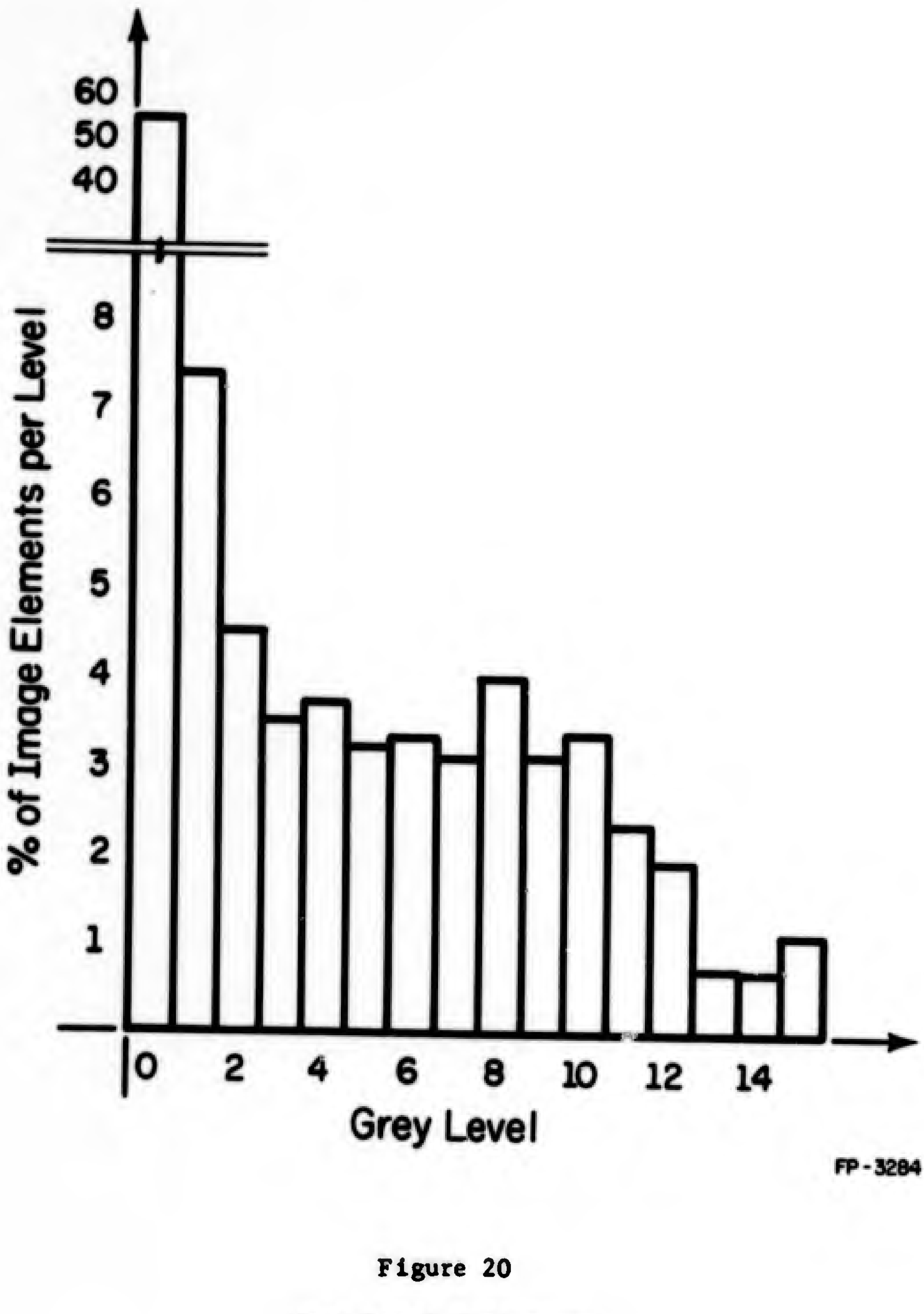

Figure 20

Grey Level Histogram

REFERENCES

1. Dunn, L. A., L. N. Goyal, B. H. McCormick and V. G. Tareski, "Parametric Description of a Scan-display System," AFIPS-Conference Proceedings, Vol. 34, 1969, pp. 187-206.

2. Hall, E. L. and S. J. Dwyer, III, "Evaluating Image Quality--A New Formalism," Comput. Biol. Med., Vol. 2, 1972, pp. 15-25.

3. Hall, D. L., G. S. Lodwick, R. Kruger and S. J. Dwyer, "Computer Diagnosis of Heart Disease," Radiologic Clinics of North America, Vol. IX, No. 3, December 1971, pp. 533-541.

4. Hall, D. L., G. S. Lodwick, R. P. Kruger, S. J. Dwyer and J. R. Townes, "Direct Computer Diagnosis of Rheumatic Heart Disease," Radiology, Vol. 101, No. 3, December 1971, pp. 497-509.

5. Hall, E. L. and A. Kahveci, "High Resolution Image Enhancement Techniques," Proceedings Two Dimensional Digital Signal Processing Conference, University of Missouri, Columbia, October 6-8, 1971, pp. 1-5-1 to 1-5-9.

6. Hall, E. L., R. P. Kruger, S. J. Dwyer, III, D. L. Hall, R. W. McLaren and G. S. Lodwick, "A Survey of Preprocessing and Feature Extraction Techniques for Radiographic Images" IEEE Transactions on Computers, Vol. C-20, No. 9, September, 1971, pp. 1032-1044.

7. Harlow, C. A. and S. A. Eisenbeis, "The Analysis of Radiographic Images," Technical Report IAL TR 11-72, University of Missouri, Columbia.

8. Lodwick, G. S., "Problems Encountered in the Computer Diagnosis of Radiographs," Proceedings Two Dimensional Digital Signal Processing Conference, University of Missouri, Columbia, October 6-8, 1971, pp. 2-1-1 to 2-1-13.

9. Nilsson, N. J., "<u>Problem Solving Methods in Artificial Intelligence</u>, McGraw-Hill, New York, 1971.

10. Preparata, F. P. and S. R. Ray, "An Approach to Artificial Nonsymbolic Cognition," UILC-ENG 70-223, Coordinated Science Laboratory, University of Illinois, Urbana, Report R-478, July 1970.

11. Rosenfeld, A. <u>Picture Processing by Computer</u>, Academic Press, New York, 1969.

REFERENCED (Continued)

12. Sutton, R. N. and E. L. Hall, "Texture Measures for Automatic Machine Recognition and Classification of Pulmonary Disease," Image Analysis Laboratory, University of Missouri, Columbia, December 1, 1971.

13. Tescher, A. G., H. C. Andrews and R. P. Kruger, "Image Processing by Digital Computer," IEEE Spectrum, Vol. 9, No. 7, July 1972, pp. 20-32.