The automatic measurement of medical X-ray photographs

W. Spiesberger and M. Tasto

The medical profession would readily agree that the preventive sector of public health care does not always work in the most efficient way. The checks required are comparatively straightforward, but unfortunately the scale on which they should be carried out annually is not usually compatible with available resources in staff and time. In X-ray diagnostics, which plays an increasingly important part in preventive medicine, the introduction of the computer has resulted in the solution of some of the problems.

The quantitative element

Between 60,000 and 500,000 X-ray records are examined annually in a modern hospital, depending on its size. These figures indicate that doctors must spend very many working hours in the interpretation of all this information. Nowadays, moreover, the records are usually not only visually examined, but attempts are made to derive more information by measuring particular objects on the image [1]. The number of working hours required for the measurement and processing of such numerical results is even greater, which rather limits the popularity of the measurement procedures. This explains the need for a partially or completely automatic data-processing package, which could be used both for the measurement of the X-ray photographs and for the processing of the resultant data.

Some examples of interesting problems include the measurement of the cardiothoracic ratio, the heart volume and other cardiac quantities [1] [2]; the determination of the volumes of the heart ventricles as a function of time, from film or television pictures of the X-ray image — by the technique of cineangiography, in which the ventricles are filled with a contrast medium; the determination of the thickness of the cardiac wall and the motion of the wall [3]; the measurement of the flow in blood vessels containing a contrast medium, using film or television recording methods [3]; the measurement of the shape and size of the carpus (wrist bones) in children in order to ascertain the extent of skeletal development [4]. In particular, the measurement of dynamic quantities by cine techniques is extremely time-consuming, because between fifty and one hundred separate images (frames) often have to be measured for each patient.

Investigation of all these kinds of measurement has demonstrated that the viewing and ‘normal’ analysis of the images — such as marking the contours of an object to be measured — are not the most labour-intensive.

Fig. 1. Television monitor with light pen, constituting part of the equipment for semi-automatic image processing. The doctor only has to trace the outline of the object (a left cardiac ventricle in the case shown) on the image screen with the light pen. The resulting coordinates appear on the screen as illuminated dots (see lower photograph) and are processed directly by a computer.
steps and do not produce the largest number of errors. On the contrary, the computation of surfaces and volumes, the processing of various kinds of data and the accurate numerical weighting of measured values for the determination of diagnostic index values are examples of operations that tend to be the most time-consuming and most frequently contain errors. Various groups, including our own, have therefore developed a number of image-processing methods that depend on the use of computers, but leave to the doctor the task of locating and marking objects of interest. A typical example is the measurement of an object from a picture on a television monitor (fig. 1). The specialist traces the outline of the object with a light pen, and the coordinates of the contour traced are simultaneously and automatically fed into the computer, which then performs all further calculations — extremely accurately and without errors. Similar processing of results can often lead to a reduction of working time by a factor of ten or more.

A further step in the direction of automation, and therefore in the reduction in man-hours, is taken by utilizing the brightness information contained in the electronic video signal. If for example the selected object is uniformly brighter than its surroundings, it is easy to provide an electronic threshold circuit to ensure that only the parts in the image above threshold are shown. Quantities such as the area can then be measured directly [8]. A similar threshold can easily be adjusted by means of a single knob for the individual patient. Fig. 2 demonstrates this method of operation.

The method is not applicable where the information comprising the image is rather more complex, and the chosen object can no longer be distinguished from its surroundings by the adjustment of a single knob, or perhaps two or three at the very most. A less straightforward procedure is then necessary, and the use of a computer with a larger memory is an obvious requirement. The program is arranged so that the brightness of the image, whose shape is irrelevant, is defined at a large number of points forming a square array. The ‘brightness matrix’ thus obtained is stored in the computer memory for further processing.

In the following sections two types of procedures are described that enable the X-ray photograph to be processed completely automatically for certain measurement applications. One type is used to determine the shape of the heart and to measure the cardiothoracic ratio, both of which are of primary importance in preventive medicine. The other procedure is used for the recognition of contours of cardiac ventricles, which are of value in a refined diagnosis of the cardiac function. In conclusion we shall look at the implementation on the computer, and at the prospects for the future.

**Cardiothoracic measurements**

The early detection of heart and vascular diseases has an important place in preventive medicine. In general X-ray photographs, electrocardiograms (ECG) and cardiophonograms are used [0] [7]. The serious nature of these diseases has led to an increase in the work required for preliminary investigations. Computer methods for the acquisition and processing of data obtained from the diagnostic procedures mentioned above are therefore of particular interest for mass screening of the general public.

![Fig. 2. Area measurement of a left ventricle (V) from a video signal (Lu)]. The threshold T and the window W can be adjusted manually. SL scan line. D diaphragm. A aorta. The logic signal II indicates whether the object sought is present (yes) or not (no). x space coordinate. The signal from the aorta does not cause an error since it appears outside the window.


The aim of computer measurements on X-ray images of the heart is to provide an objective, reproducible and quantitative description of the image. In mass X-ray screening the images obtained are in the AP projection (anterio-posterior, i.e. from the front and perpendicular to the chest). The earlier work in our laboratories and elsewhere has been on automating the determination of the cardiothoracic ratio (i.e. of the sizes of the heart and thorax) and on the determination of the shape of the heart — both comparatively straightforward measurements. In clinical practice the cardiothoracic ratio is taken as a basic quantity; deviations from the ‘normal’ ratio indicate changes in the heart. Congenital heart defects in children, for example, can be inferred from the shape of the heart [11].

The cardiothoracic ratio

Several methods for the determination of the cardiothoracic ratio, as defined in fig. 3, are known, but the equipment and procedures required differ somewhat. H. C. Becker et al. [8] determine the width of the heart and the thorax from a ‘signature’ curve. The computer determines the signature curve by an integration of the brightness values along a strip, without considering other details of the image. The signature curve of an \( n \times m \) image is represented by the function

\[
S(k) = \sum_{i=1}^{m} I(k, i), \quad \text{with} \quad 1 \leq k \leq n,
\]

where \( I(x, y) \) is the brightness at the point \((x, y)\). The width of the heart and thorax can be determined from the profile of the signature curve. The method does not of course yield exceptionally accurate values but the inherent error does not amount to more than a few per cent.

The methods that we have developed for the measurement of the cardiothoracic ratio and for the description of the shape of the heart originate in principle from a contour image. Processing this contour informa-
tion yields sufficient information to give the maximum extent of the heart and thorax in the transverse direction. The left and right halves of the cardiac contour are scanned in the transverse direction with the object of finding the maximum width. The width of the thorax is determined just above the diaphragm. The ratio is the required cardiothoracic ratio.

Images containing only a contour represent about a hundredth of the amount of information in the original complete image, and can therefore be processed very much faster.

For investigations on a large scale, the ability to determine the cardiac contour completely automatically is a good starting point. The classification of the measured contour is also an important point for diagnosis; however, a description of the parameters of the contours cannot then be avoided. Both points are discussed briefly below.

The cardiac contour

The universal image-processing methods described in the literature are not suitable for the determination of the cardiac contour, because they require a great deal of computer time. Simplified methods, such as those using a fixed brightness threshold, again have the disadvantage that they can only be used if the X-ray photographs are standardized. The size and the position of the patients, together with the exposure time and the development of the film, have a considerable influence on the content of the image and its contrast. Consequently a fixed brightness threshold cannot be used. We have therefore developed a method\(^{[9]}\) in which an individual threshold is derived afresh for each image from a histogram of the brightness (fig. 4).

Using known methods the computer then determines a binary image field from the derived threshold (‘0’ for points of brightness below the level, ‘1’ for the other points). A boundary contour between the heart and lungs is now considered to have been found if at least three successive ‘0’ points are found when scanning from inside to outside in the coordinate direction most perpendicular to the estimated contour. With this criterion it is always certain that a connected ‘0’ region will be found as a boundary (figs. 5 and 6). The boundaries of the heart on the upper and lower sides cannot be derived from the X-ray image because the appropriate contours are not shown. It is therefore necessary to try to obtain them artificially. The lower boundary of the heart is defined by the line connecting the left- and rightmost points of the cardiac contour.


![Fig. 6. Example of the search for a cardiac contour. Left: original X-ray photograph; right: the contour found by using a variable threshold and a binary field (figs. 4 and 5), which separates the heart and lung areas from each other.](Image)
right-hand corner points where the heart, lungs and diaphragm meet. The computer finds these two corner points by measuring the distances between the appropriate part of the contour and a fixed reference point (fig. 7). This distance is a minimum at the desired corner point. Our current program uses the smallest horizontal distance to define the boundary on the upper side. This method enables a closed cardiac contour to be determined in a simple way (fig. 8). The contours obtained in this way can be used for the measurement of the cardiothoracic ratio, and also for classification purposes.

The parametric description of the cardiac contours

R. P. Kruger et al.\textsuperscript{[10]} report that in heart diseases associated with a change in shape, it is possible to make an automatic diagnosis that in some respects will give more accurate results than the evaluation of X-ray photographs by a number of doctors. They have used a number of very different lengths, distances and angles as criteria.

C. T. Zahn and R. Z. Roskies\textsuperscript{[11]} have described a method for the coding and classification of plane closed curves, that is independent of the position, orientation and size of the curves. If this method is applied to cardiac contours it should be possible to correlate automatically certain heart diseases or defects with the shape of the heart. Such a diagnostic technique does of course require that the classification programs should be applied to a very wide range of material.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{Fig. 7. Determination of the lower and upper boundaries $D_L$ and $D_U$ of the heart from the minima of $d_i$ or $d_j$ and $d_k$. $P_0$ fixed reference point. The method of contour determination is shown in figs. 4 and 5.}
\end{figure}

In the method of coding that we have developed, the contour is traced out in a clockwise direction and the change in direction is continually evaluated as a function of the distance travelled. The change in direction is equal to the angle between the local tangent and the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8.png}
\caption{Fig. 8. Left: cardiac contour determined completely by the computer. The two horizontal lines establish the width of the heart. The width of the thorax is the distance between the vertical lines. Right: original photograph with the derived contour and distance lines drawn in.}
\end{figure}
tangent at the chosen starting point; the total contour length corresponds to an angle of $2\pi$ radians. The periodic shape function derived from this calculation is expanded in a Fourier series:

$$\Phi^*(t) = \mu_0 + \sum_{k=1}^{n} A_k \cos(k\theta - 2\pi k).$$

The function has been defined in the interval $(0, 2\pi)$ and is equal to zero at the end points. The pair $A_k, 2\pi k$ are known as Fourier descriptors, $\mu_0$ is a constant term which is related to the chosen starting point. The required details relating to the shape are supplied by the Fourier descriptors. As is always the case in Fourier analysis, the first terms of the series contain the 'coarse' information whereas the fine detail is contained in the terms of higher order. As the heart has no sharp edges or protuberances, a small number of terms will usually be sufficient. The Fourier descriptors that are necessary to describe the cardiac contour constitute a much smaller quantity of data compared with the contour itself. Fig. 9 shows three contours that have been completely automatically constructed from 5, 10 and 100 pairs of descriptors.

![Fig. 9. The three displayed cardiac contours have been constructed with the help of 5, 10 and 100 pairs of Fourier descriptors. Small numbers such as 5 and 10 are essential if the information is to be used for classification purposes. In this way an efficient data reduction can be achieved.](image)

A great deal of importance is attached to the reduction in the amount of data, because the amount of computer work in classification programs increases more rapidly than linearly with the number of parameters. The result of a computer analysis must of course be produced in a reasonable time, i.e. a time comparable with that which a doctor would need for the diagnosis. This consideration makes the parameterization of the cardiac contour a virtually essential aid in classification.

Computer determination of ventricle contours

The determination of the left-ventricle cardiac contour has three objectives: the determination of the volume as a function of time, the measurement of the wall movement at a number of places and the observation of wall thickness as a function of time. The results obtained are used for the refined examination of the cardiac function, in which more quantities such as the blood pressure and its variations are combined with the volume data. The ventricle is made visible by the injection of a contrast medium via a catheter. The image is usually recorded at a speed of 50-100 frames per second; the normal procedure is to record a single complete cardiac cycle, so that a filming time of one second is adequate. In fig. 10 two photographs of a ventricle taken in rapid succession are shown. In general, other objects such as the diaphragm, ribs and aorta will be visible in the recorded image. In this case it will be necessary to apply a more complicated data-processing method than the simple threshold method.

The block diagram of our data-processing method is given in fig. 11. The first stage of the procedure is a coarse search for the contour, characterized by the use of only $32 \times 32$ image points during the scan, i.e. a low resolution. In the second stage the contour is more accurately located. Starting from the coarse contour already found, the computer searches the first frame for new position coordinates with a higher resolution. Then the complete film strip is scanned, one frame at

---


Fig. 10. Two X-ray photographs of a left cardiac ventricle that has been filled with a contrast medium. The time that has elapsed between each exposure is about 20 ms. 

Fig. 11. Block diagram of the method for automatic determination of a left cardiac ventricle. The input information is on M X-ray frames; \( n \) is the frame number. The first step in the procedure is the coarse search; the high-resolution search occurs in the second, iterative step.

Fig. 12. The graphs give the brightness variation on approximately 50 successive photographs, in the indicated positions on the X-ray image of a left cardiac ventricle.
Fig. 13. The first method of coarse searching yields a binary field. The circles are the points where the threshold in the brightness change has been exceeded (level 'I'). The squares are points to which a level 'I' has been erroneously ascribed (e.g. by noise) and they could be eliminated later by a 'cleaning' process.

noise or the intrusion of the edge of the picture; these can be eliminated by using special noise-suppression methods ('noise cleaning'). A contour can be derived from the binary field, since the computer takes every 'I'-0' transition it encounters while it scans radially outwards as a point of the contour. The computer starts the scan somewhere close to the 'centre of gravity' of the field of 'I' values.

The second method for low-resolution search is the 'template' method. In this case the frame to be processed is first transformed into a 'dash-point figure', which implies that all the contours (including those of objects not required) are determined and reproduced initially in the form of dashed lines. The computer then moves a template of the required object over the dash-point figure, and the object is considered to have been found when the deviations between template and object are as small as possible. The distances between different points on the template and those points that lie closest on the contour of the given figure are taken as a measure of the deviation. An example of such a dash-point figure with a ventricle template mask that has been moved across it is depicted in Fig. 14. The distance lines are also shown. In this idealized example the template is of exactly the same shape as the desired object; this never occurs in practice, of course. The distances decrease to zero when the template is accurately located over the object. Fig. 15 shows a situation in which there is still a large error in the position of the template, as can clearly be seen from the distance lines.

High-resolution search

The contour that has been found with the help of one of the two coarse methods is used as starting material for the fine search. Three types of prior data are derived from the coarse contour: the direction and the magnitude of the interval to be searched and the sign of the

Fig. 14. The second method of coarse searching uses a template. A cardiac-ventricle template (the thick brown line) is shown as an example. This is 'moved' close to the object under investigation by the computer. The distance lines are therefore short. The case shown has been idealized; in practice the template and object will not have precisely the same shape.

Fig. 15. The template is still some way away from the object. The distance lines are much longer than in the situation shown in Fig. 14.
brightness gradient to be determined [14]. In fig. 16 a contour found by the coarse method is drawn, with a normal constructed by the computer; the normal establishes the direction of search for a new contour point. The magnitude of the interval to be searched is also known to the computer, as the maximum uncertainty in the position of the coarse contour.

When a series of frames are processed, the computer always takes the contour from the preceding frame as the coarse contour for the ensuing fine search, as we saw above. The maximum uncertainty follows, in this case, from the maximum rate of travel of the ventricle wall and the frame rate.

The search for a contour point in a fixed interval occurs as follows. The computer determines the brightness gradient, which is scanned radially from inside to outside in the search direction. The point where the gradient has the greatest positive value is the point that the computer is looking for. The sign of the gradient obtained is the means by which the computer distinguishes the required contour from undesirable overlapping objects, such as the diaphragm. The brightness must always decrease at the contour being searched for when the scan goes from inside to outside.

In fig. 17 two heart-ventricle contours have been drawn on the original X-ray photograph. These contours were determined fully automatically by the computer. The boundary line between aorta and ventricle can be deduced approximately by searching at the side of the ventricle directed towards the aorta for the place where two contour halves that lie opposite each other have the smallest spacing (the short dashed line). Finally, for computing the heart volume, the computer constructs the axis of symmetry of the contour (the long dashed line). In the computer program it is assumed that the cross-section across the long axis of the ventricle is elliptical or circular, depending on whether the computer has access to images in two projection directions or only in one direction (as is most usual).

Current implementation and future prospects

The methods that have been described so far can be executed on medium-sized computers with a memory capacity of 32 kbyte or more. The programs should ideally be formulated in 'machine-independent' languages; the methods may then be implemented with few compatibility problems in most medical centres. The digitizing of images, as well as the presentation of processed images and results, can be separated from the pure data-processing activities. Standard television equipment can be used for digitizing and presentation. In all our ventricle methods only relevant information from each image is digitized and this results in processing times of only a few seconds. The cardiothoracic procedure with its associated parameter description always utilizes the same number of image elements. The rather computation-intensive algorithm for the classification of the contour information results in a computing time of several minutes for each image.

The determination of the ventricle contour and the cardiothoracic measurements dealt with in the earlier sections are only two examples from a multitude of possible medical applications. A number of the image-processing operations used are in many cases identical and are employed for different purposes in different applications. It seems desirable to give a modular structure to a general data-processing program for X-ray photographs, to avoid having to re-program each image-processing routine at every changeover to a new field of application. With a suitable range of appropriately designed image-processing programs it would then be possible to test the solution of new problems with the existing modules. The time required, compared with the current situation (writing a complete program, testing, modification, etc.) would be much shorter. If the way to a solution was found by experimenting with
Fig. 17. Two examples of cardiac contours that have been located automatically, both displayed on the original X-ray photograph. The short dashed line determines approximately the boundary between the aorta and the cardiac ventricle. The long dashed line is an artificial axis of symmetry, which the computer uses for the continuous, completely automatic computation of the ventricle volume. In the right-hand photograph, the ventricle is in its contracted state (systole) and in the left-hand photograph it is in its expanded state (diastole).

Summary. X-ray diagnostic methods are in need of automated image-processing procedures (= measurement of photographs + processing of the results), especially for preventive health care. Program packages, both existing and under development, for selection, recognition and digital processing are discussed; the emphasis is on cardiothoracic measurements and the determination of cardiac-ventricle contours. The cardiothoracic measurements concentrate on the automatic determination of the width ratio from the contour measurements in AP projection. Further data reduction, necessary for shape-classification investigations, is accomplished by parameter representation with Fourier descriptors. The contour recognition — by a gradient method — is performed iteratively on a series of film images of one cardiac cycle; the computer finds the required initial contour with a threshold or a template method. Noise errors can be eliminated.

The data-processing programs, a separate program for the particular case could always be written later — which would not take long.

The time and effort required, in the short term, for the preparation of such a useful general image-processing program package, would be completely recovered in the long term by the resulting possibilities for rapid and flexible image-processing in many medical (and non-medical) situations. We hope that this more general solution to the problem will become reality in the not-too-distant future.