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AUTOMATIC 3D RECONSTRUCTION OF CORONARY ARTERY SEGMENTS IN PATHOLOGY

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ABSTRACT—Recently, owing to the increasing processing power of digital computers and graphic peripherals, a major interest has developed in the reconstruction of internal body structures so as to create *digital objects* which can be handled and displayed using techniques developed in Computer Graphics.

In this paper we present a method for automatic reconstruction of coronary artery segments from serial slicing in Pathology. The resulting 3D model can be handled and displayed using computer graphics techniques. Results have shown that the proposed system can be a useful tool in the study of coronary artery disease.

INTRODUCTION

Coronary occlusion is a common cause of myocardial infarction and is often fatal. Ischaemic heart disease was responsible for approximately 160,000 deaths in England and Wales in 1985, nearly 27% of all deaths that year [Office of Population Censuses, 1985].

The degree of stenosis, measured as reduction in lumen size, has been a key concept for the study of arterial diseases in general. Methods for estimating cross-sectional surface area have varied from counting squares enclosed by outlines [Sissons,1963] to paper-weighing techniques [Bell et al, 1967], and from planimeters [Aherne, 1971] to image processing [Gore, 1979]. Understandably, computer techniques have been increasingly used in the last few years. Nevertheless, whichever methods are used they concentrate mainly on the slide-by-slide study of arterial segments.

In this paper we describe the method we have developed for the reconstruction of coronary artery segments from sequences of cross-sections.

Once reconstructed the segments can be handled, viewed, sliced in several directions and re-assembled using the computer system we have developed which is described elsewhere [Moura, 1988]. Geometric parameters such as areas, volumes and distances can be easily measured.

PRELIMINARY CONSIDERATIONS

In this paper the extraction of information for the reconstruction of coronary artery segments from series of cross-sectional slides is considered. An example of such a series can be seen in Figure 1. It consists of ten slides taken at equally spaced depths. This series of images has been selected as very representative of the type of data this work is concerned with.

The coronary artery slides used in this paper have been obtained using a procedure described in detail by [Moura, 1988]. Basically, the coronary arteries are dissected from hearts obtained at autopsy, fixed, processed and thinly sliced using a microtome. Each slice is then attached to a rectangular piece of glass and covered with another piece of glass, smaller and much thinner.

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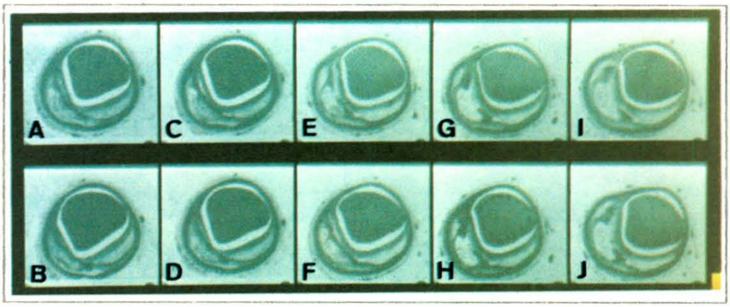

Figure* 1 *A Series of Cross-Sections.* *The images from (a) to (j) are coronary artery cross-sections after being digitised.

There are several levels of detail in the vessel structure. Although these details can convey important information to the pathologist's eye and the inner compartments may be important for some studies [Davies and Thomas, 1985 - Hangartner et al, 1986], this work is restricted to the structures defined by what we will refer to as the external and internal arterial walls — the outer contour of the *tunica media* and the contour defined by the *tunica intima.*

The reasons for this restriction are that: a) wall contours are more tractable than general, sometimes very fuzzy, compartments; b) arterial walls are the most important arterial structures and will always be the first structures to be searched for; c) in functional terms blood flow through the vessel is critically dependent on the lumen size, and d) the level of three-dimensional detail the present computer system can represent is resctrited by the 64^3-voxel Digital Scene. This resolution is below that required to represent finer details accurately.

A block diagram depicting the operations performed for coronary artery segment reconstruction is shown in Figure 2.

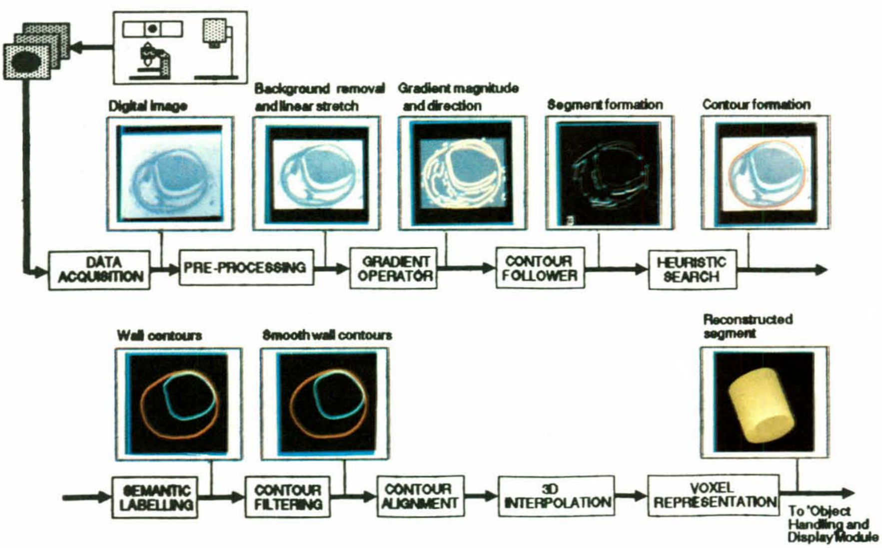

Figure 2 Block Diagram for 3D Coronary Artery Segment Reconstruction.

DATA ACQUISITION

Each slide is photographed under the optical microscope using a 35-mm camera and 100 ASA black and white negative film. The 35-mm negatives are enlarged to the size of 5"x7" on glossy paper and the photographs are digitised into the computer by means of a Panasonic 1600 camera with a Vidicom cathod-ray tube. Although the camera's resolution is of 770 columns and 575 lines, these are decimated so that the usable final picture consists of 222^2 pixels. The pixel values are in the range [0,255].

PRE-PROCESSING.

Once the images have been digitised into the computer they are pre-processed in order to enhance image quality. In this work pre-processing consists basically of two steps: background removal and histogram stretch.

Background Removal.

Background removal is intended to compensate for variations in lighting that may have occurred when digitising the image or photographing the slides. It is assumed that any possible trend in illumination is linear in i and j. The trend is estimated using Least Squares techniques and subsequently removed [Moura, 1988].

Histogram Stretch.

Once trends in background have been removed the histogram of intensities is stretched. The aim of this operation is twofold. Histogram stretch not only enhances visual contrast but it can also be used to bring together some data standardisation [Moura, 1988].

AUTOMATIC CONTOUR DETECTION.

The input data to this stage are the pre-processed images. These are well-balanced and contrast-enhanced images in which coronary artery cross-sections appear against a lighter background. Images in Figures 1 are very representative of the type of images to be processed and must be analysed visually in order to create a feeling about the task to be executed automatically.

Here, it is more important to comprehend the general difficulties involved in characterising the contours for automatic detection than to be strictly accurate. In these images, for example, the external and internal wall contours — the contour of the tunica adventitia and the contour defined by the tunica intima — are *roundish* and the contour lines appear *reasonably clear*. However, some *large gaps* may exist due to either superimposition of structures or image noise.

Any edge detection method which can take advantage of this *a priori* knowledge of contour characteristics is a good candidate for the application in view. A particularly strong boundary detection method when contours are of known shape is given by Heuristic Search.

The application of Heuristic Search to the task under consideration is discussed in detail by [Moura, 1988]. It is basically a three-step method. In the first, the original image is smoothed in order to remove unwanted details and a gradient operator is applied to it.

The brighter the pixels in the resulting gradient magnitude image are the higher their likelihood of being part of edges. The second step explores this fact using bright gradient pixels as starting points for a contour-follower algorithm so that long one-pixel-wide edge segments are formed.

The final step in the procedure is to connect the edge segments using some geometric criteria to form closed set of segments, called paths. A cost function is associated to each path and a contour is a minimum cost path. In order to succeed the cost-function must be chosen in such a way that it is minimised by contours with the desired forms — in the case in view circle-like shapes. Segment connection is performed by means of Ferguson Curves [Ferguson, 1964] so that the connecting lines tend to follow the general contour behaviour [Moura, 1988].

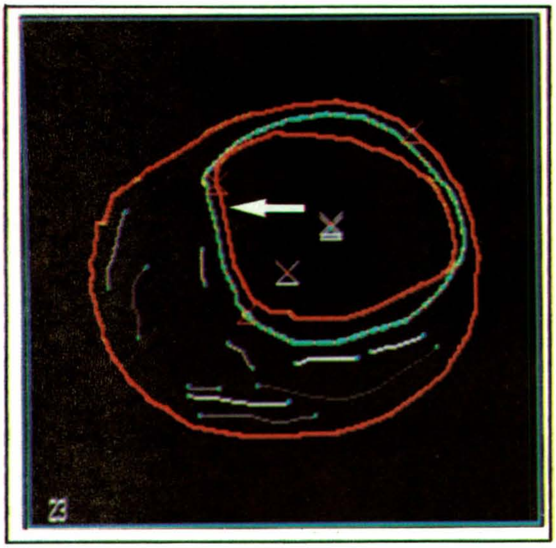

Figure 3
The Detected Contours.
The three detected contours are the minimum cost paths for the segments they use.

AUTOMATIC CONTOUR LABELLING.

Heuristic Search has been successfully used to detect the arterial wall contours. However, it has also detected a third contour. This contour — marked by an arrow in Figure 3 — is caused by coagulated blood which has shrunken during specimen preparation and is usually present in the type of slide under consideration. This contour must be disregarded as it does not bring any useful information.

This fact highlights the need for some sort of semantic contour classification which allows that the external and internal wall contours be properly recognised and labelled.

The approach we have devised for automatic contour classification is based on two contour features, both contextual. The first is the gradient direction — inwards/outwards — in relation to the contour centre. We define this direction as inwards if the contour defines a structure which is lighter than its surroundings and outwards otherwise. The second contour feature is its position relative to other contours.

The gradient direction can be detected by analysing the straight line which goes from the *contour centre* to the contour pixel with the highest gradient magnitude value. If the angle between this line and the gradient direction at the brightest pixel is less than $\pi/2$ then the gradient direction is outwards, otherwise it is inwards. The choice of the highest gradient magnitude pixel on the contour is due to the fact that this pixel is most likely to be at a very well defined edge segment.

The relative contour position can be extracted by straight lines that go from the bottom of the image to its top through each *contour centre.* If a number is assigned to each contour and if these numbers are recorded as the contours are intersected by the straight lines, the resulting *Contour Position Strings* will yield information regarding their relative position.

These two procedures are combined so that the required contours can be found. A major factor for these techniques' success is the choice of the *contour centre* required for both algorithms. If this point is too close to the edges it may cause errors in both cases. We have developed a very reliable technique for fitting a circle to a set of points using Least Squares. This technique is described in full by [Moura, 1988] and is used to determine the contour centres for contour labelling.

CONTOUR FILTERING.

Wall contours detected by the automatic procedure tend to be somewhat rough, as can be seen in Figure 4. If the edges in the original image are noisy then the contour may be inaccurately detected, as in Figure 4a. However, as pointed out earlier in this paper, arterial wall contours are expected to be smooth. This property can be used to correct regional roughness.

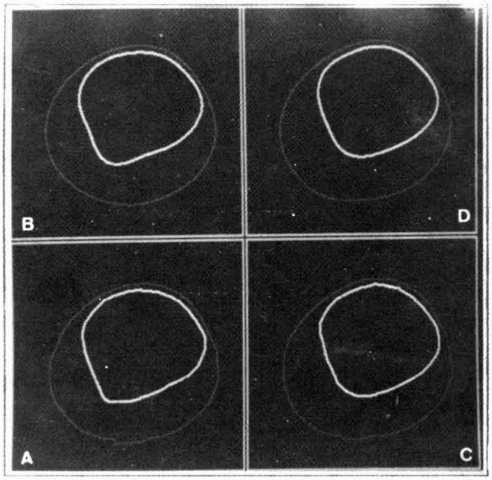

Figure 4
Contour Filtering.
This technique can be used to generate smooth contours (b) and (d), from the detected contours.

We have developed a technique for closed contour filtering which fits smooth, *piece-wise polynomial-radius contours*, to the original curve in the Least Squares sense. This contour filtering technique is discussed by [Moura, 1988].

AUTOMATIC CONTOUR ALIGNMENT

Since cross-sectional slides are produced by actually slicing the block of biological material, the physical relation between slides is lost. Although it is possible to mark the specimen before slicing and use these marks for later positioning, or even re-align the contours by visual match, automatic contour alignment must be implemented if the system is to be used on a day-to-day basis.

We have decided to use the external wall contour for aligning the arterial wall contours. The two external wall contour centres in the two slices under consideration are assumed to coincide and a *best fit* is searched for. The best fit is assumed to be achieved when a cost function η is minimised:

$$\eta = a_1 E + a_2 D,$$

where E is the mean square difference between external contour radii, D is the distance between inner contour centres and a_1 and a_2 are application-dependent constants.

Since the wall contours are θ-contours with radii defined for every one of 360 degrees, the steps above can be easily implemented [Moura, 1988].

THREE-DIMENSIONAL INTERPOLATION

In order to create a Voxel Space representing the coronary artery segment, it is necessary to use some interpolation technique. Instead of using some general surface tiling technique it is possible, once again, to take advantage of the fact that wall contours are described by θ-contours. A contour on any plane between two known θ-contours can be approximated by interpolating the two adjoining θ-contours.

One example of the final coronary artery segment reconstructed using this technique is shown in Figure 5.

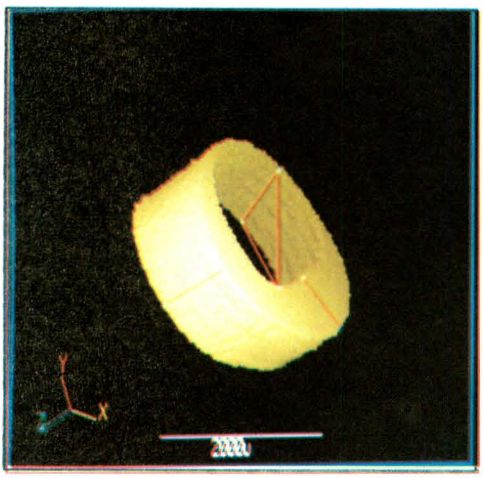

Figure 5
The Reconstructed Segment.

CONCLUSIONS

In this paper we have described an implementation for the reconstruction of Coronary Artery segments from a series of slides in Pathology.

The most fundamental step for the success of this implementation is the automatic detection of the arterial wall contours. These are assumed to be *roundish* or — more precisely — the *most roundish* structures in an image. The method uses a cost-function which measures roundness and that is used to locate the wall contours.

This assumption restricts the classes of images the system will successfully process but on the other hand allows that wall contours with very wide gaps be detected.

The use of the contour filtering technique we have developed has allowed that the condition of roundness be monitored and automatically corrected. Moreover, the use of θ-contours permits that wall contours be easily aligned and — more importantly — easily interpolated.

Serial slicing itself poses many causes for concern, since exact alignment is impossible to achieve and the several existing alignment methods intrinsically assume that the segments are somewhat straight and that the plane of slicing is orthogonal to the segment. Although this is the best assumption that can be made it will never be good enough in the case of tortuous arteries.

Another problem presented by serial slicing is that each final slice may have been distorted either by pressure exerted on the specimen by the microtome or when the slice is handled for slide mounting. These distortions cannot be directly measured and estimating them is not an easy task. Such distortion contributes to unreliability, even though for most of applications it is assumed that the overall effect is not significant [Aherne, 1982].

Unfortunately, so far there is no alternative method which can be used for generating arterial cross-sections at a good resolution and therefore serial slicing is bound to be used for some more years to come.

ACKNOWLEDGEMENTS

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