

## MODEL DRIVEN VISUALIZATION OF CORONARY ARTERIES\*

G.T. Herman<sup>1,2</sup>, L. Axel<sup>1</sup>, R. Bajcsy<sup>2</sup>, H. Kundel<sup>1</sup>, R. LeVeen<sup>1</sup>, J.K. Udupa<sup>1</sup>, and G. Wolf<sup>1</sup>

Department of Radiology  
University of Pennsylvania  
3400 Spruce Street  
Philadelphia, Pennsylvania 19104

Department of Computer and  
Information Sciences  
University of Pennsylvania  
Philadelphia, Pennsylvania 19104

### ABSTRACT

In a joint project between the Departments of Computer and Information Sciences and Radiology we are applying techniques of artificial intelligence to improve clinical performance as related to coronary arteries. Specifically, we are investigating how images from intravenous digital subtraction angiography (DSA) can be enhanced so that their efficacy for lesion detection and quantitation becomes comparable with that of the more dangerous procedure of selective coronary arteriography. The enhancement techniques (which include algorithms for three-dimensional vessel detection, reconstruction, and display, as well as for accurate lumen size estimation) are based on models of (i) the three-dimensional topological structure of the coronary arterial tree, (ii) myocardial dynamics, and (iii) the x-ray imaging process involved in producing digital subtraction angiograms. The evaluation of these model driven visualization techniques is done by the standard psychophysical method of Receiver Operating Characteristic (ROC) analysis applied to observer performance tests on images from an animal coronary atherosclerosis model.

### I THE MEDICAL PROBLEM

Conventional x-ray imaging uses photographic film or fluorescent material to produce an image of the x-ray shadow cast by the body. The intensity of the x-rays exiting the body along a given path through the body from the x-ray source to the detector will be dependent on the total absorption along the path. Structures that are much more absorbing of x-rays than the surrounding tissues will be easily identifiable in the x-ray images. However, the superposition of shadows makes it very difficult to image structures that differ little from their surroundings, such as the coronary arteries.

Atherosclerotic coronary artery disease is a major public health problem. A noninvasive method of diagnosing coronary artery disease and

assessing the results of treatments, such as bypass graft surgery, would be a major contribution. Conventionally, coronary arteries are studied by selective arteriography, a somewhat dangerous procedure in which a catheter inserted into a specific artery is used to deliver contrast material to improve visualization of the lumen. See Fig. 1 for an example of a selective arteriogram. It has been asserted that coronary arteriography has limitations in diagnosing vascular disease (see, e.g., [1]).

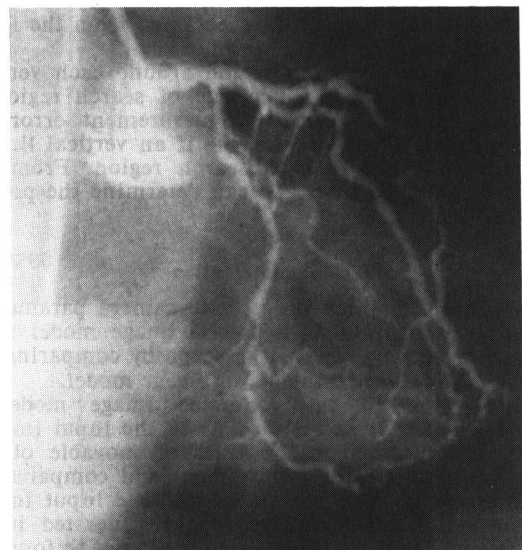


Figure 1

Digital subtraction angiography (DSA) is an alternative and much less invasive test (see, e.g., [2]). X-ray images are obtained prior and after introduction of contrast into the circulatory system. The x-ray images are electronically detected and the detected x-ray intensities are digitized as functions of position. By knowing the initial x-ray intensity without contrast, the summed x-ray absorption of the contrast material alone can be calculated. If the patients remain motionless, the resulting subtraction image will have the shadow of nothing but the contrast material, and so in principle a much lower proportion of contrast to blood need to be used than in selective arteriography. One can possibly do with-

\*The research reported in this paper is supported by National Institutes of Health grant HL29985.

out delivering the contrast to a specific site, and thus eliminate the need for insertion of the catheter into a specific artery and allow a simple intravenous injection of contrast. The quantitative capabilities of DSA offer the possibility of finding the relative and even absolute cross-sectional lumen area of the coronary vessels without requiring sharp edge definition. This could provide a more accurate method than conventional selective arteriography, which relies on detecting variations in the silhouettes of vessels. In particular, the visual representation of computer-produced absolute measures of cross-sectional areas is likely to be a more repeatable and reliable predictor of the hemodynamic impact and of the prognostic significance of coronary stenosis (narrowing) than the currently commonly used subjective visual estimate of "percent stenosis" [3]. On the other hand, the image quality in DSA is inferior to that obtained with selective arteriography. Particular limitations are decreased spatial resolution, and problems in separating overlying contrast in cardiac chambers with intravenous injections. Hence the DSA images by themselves do not contain information for visualization that is competitive with selective arteriography. On the other hand, a great deal of a priori knowledge exists (such as gross anatomy) and can be put into models which provide information for driving visualization procedures.

The problem that we are investigating is the following: "Can the application of model driven visualization procedures to images produced by DSA improve their clinical efficacy to or above the level of the efficacy of the more dangerous procedure of selective coronary arteriography?"

The phrase *model driven visualization* is used here in a standard sense as defined, for example, by Ballard and Brown [4]: "high-level models in the knowledge base generate expectations as predictions of geometric, segment, or generalized image structures in the input".

## II VISUALIZATION TECHNIQUES

In conventional coronary arteriography, projection images are obtained from several directions on high contrast film. The outline of the vessels is studied and the severity of local vascular disease is assessed by the degree of narrowing of the outline. As atherosclerotic lesions are commonly eccentric and irregular, several projections are made, and the one showing the greatest degree of narrowing for a given lesion is used to estimate the severity of the lesion. The size of the lesion often tends to be underestimated from the images, either because the lesion was not imaged tangentially to its dimension of greatest narrowing or because the local narrowing was part of a longer segment of more diffuse disease. On the other hand, post-stenotic dilation could also lead to overestimation of degree of stenosis. See e.g., [3] for a discussion.

In DSA, a bolus of contrast medium is injected intravenously and sequential digitized fluoroscopic images are obtained as the bolus of contrast medium flows through the central circulation. To improve the images, initial images, without contrast medium present (masks), are digitally subtracted from the later images.

Two major difficulties with DSA are that (i) the vessels overlay the beating heart, with contrast material in the chambers superimposed on the vessels, and (ii) images are less sharp than those obtained with selective arteriography. A potential advantage of DSA is that the quantitative nature of the image data may allow direct calculation of the relative cross-sectional areas of the vessel lumens from the integrated profile of the vessel image. This would allow detection of regional vascular disease without requiring sharp edge definition, and might even permit more accurate assessment of severity of lesions than conventional arteriography. In order to realize this potential, very accurate digital masking must be performed, including: nonlinear (logarithmic) subtraction, correction of possible effects from x-ray beam hardening by dense absorbers, such as bones, EKG gated imaging to include the effects of cardiac motion, and a model for the contrast in the cardiac chambers. The hierarchical masking procedure which we now describe is based on models of both the myocardial dynamics and the x-ray imaging process involved in DSA.

Our time variant subtraction mask for the digital imaging is built from three components. The first component of the mask includes the time invariant structures, such as bones and soft tissues of the chest wall and abdomen (the studies are performed during suspended respiration to avoid respiratory motion). The second component of the mask incorporates the moving portion of the image before the injection of contrast, as a function of phase of the cardiac cycle (determined by EKG gating). The third component of the mask includes the non-cyclic effects of the cardiac chambers (for studies made with intravenous injections). These are modelled as four chambers with cyclical dimension changes, each with an average contrast concentration that changes smoothly with time but is uniform within each separate chamber at any particular time.

The production and subtraction of masks provide us with images which are supposed to be projection images of the three-dimensional vessel structure only. Since this can only be achieved approximately, two-dimensional image processing applied to these images can improve their efficacy. In addition to standard image enhancement techniques, we are investigating the usefulness of a model driven detection system which makes use of built-in knowledge of properties of the appearance of objects it is supposed to detect. We are adopting the general approach of [5], which reports on a model driven approach for finding roads in satellite images, but use of course a different model which incorporates the expected appearance of vessels in DSA images. Such image enhancement techniques are needed, since in the unenhanced

images the "noise" is likely to be high enough to cause local areas in coronary arteries to be below the threshold of observer detectability. Model driven two-dimensional enhancement can be used to produce new (high contrast) images.

To implement the further processing of the images, to create new images incorporating information on the cross-sectional areas of the vessel lumens, several steps are necessary. First, the 3-dimensional orientation of the vessels must be determined from the projection images. While this would not be possible for a given general set of limited projection images, we can use our knowledge of the special properties of the vessels to help us, including the connectedness of the vessels, the limitations on numbers and angles of branches, and the fairly standard arrangement of the larger vessels.

Thinning algorithms that we have developed for the analysis of carotid arteriograms are used to determine the local orientations in 3-dimensions of the lumens of the vessels. The integrated area beneath the profiles of the vessels at right angles to the direction of the axis is determined in the projections and the results are correlated with the 3-dimensional orientations of the vessels to produce a map of estimated vessel lumen cross-sectional area along the vessels. This information can be displayed in several ways. The area can be encoded on either a gray scale intensity or a pseudo color scale and used to modify the appearance of the vessel in the display. Area can be displayed relative either to an overall scale or to the segments of vessels between branch points. The area information can be used as an overlay on the original images of the vessels. It can also be used in conjunction with the 3-dimensional map of the vessels to create an interactively rotatable 3-dimensional display of the vessels, as illustrated in Fig. 2, see [6] for details.



Figure 2

We now briefly discuss three of the techniques that are used to achieve the aims outlined above.

Three-dimensional reconstruction from multiple projections is now a well-developed field [7]. It is however well known that accurate reconstruction from a few projections is not possible unless a great deal of a priori knowledge is available. In the project under discussion we make use of a priori knowledge based on a model of the topological structure of the coronary arterial tree, as well as the knowledge that arteries lie on the surface of the myocardium.

Both in the 3D reconstruction (where a model of the tree has to be matched with the coronary tree of a specific individual) and in the modelling of myocardial dynamics (for the production of subtraction masks) we make use of an elastic deformation method, in which we map a reference object onto an actual object under the assumption that the reference object is made from an elastic material which is then deformed to become similar to the actual object [8]. The mapping of choice is one which minimizes a cost function of the form "DEFORMATION minus SIMILARITY".

We complete this section with an example showing why we need model driven variants of general algorithms. For accurate "lumen cross-sectional area" estimation, we need to define the "direction" of the vessel. This we do by using a medial line to determine the direction. In Fig. 3a we show a DSA image of a common carotid artery with a very noticeable stenosis. To find the medial line we first applied thresholding to produce Fig. 3b. Our model driven adaptation of the parallel thinning algorithm reported in [9] produced Fig. 3c which shows an acceptable representation of the direction of the vessel all along its length. The unaltered algorithm of [9] could not distinguish the stenosis from a branch (since it had no knowledge of such things) and produced the inappropriate (for our application) medial line shown in Fig. 3d.

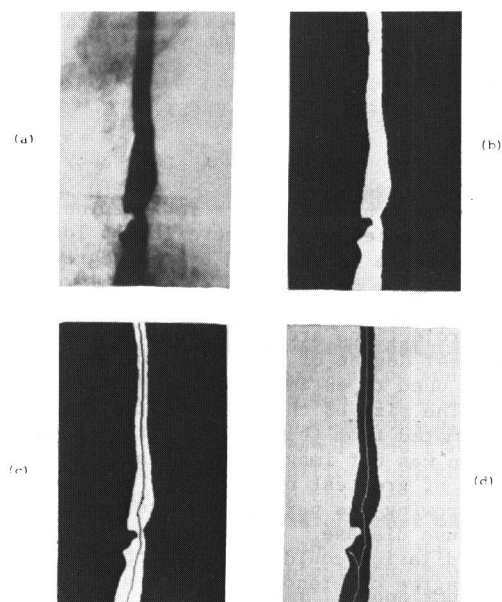


Figure 3

The medial line so obtained can be chaincoded [10], and thus easily rotated by  $90^\circ$  in both directions at any point along its length (see Fig. 4a), defining two "normals" to the direction at that point. The intensity values in the original (Fig. 3a) at points corresponding to points on these normals can be plotted (Fig. 4b), and the area under this curve can be used as a measure of the lumen cross-sectional area.

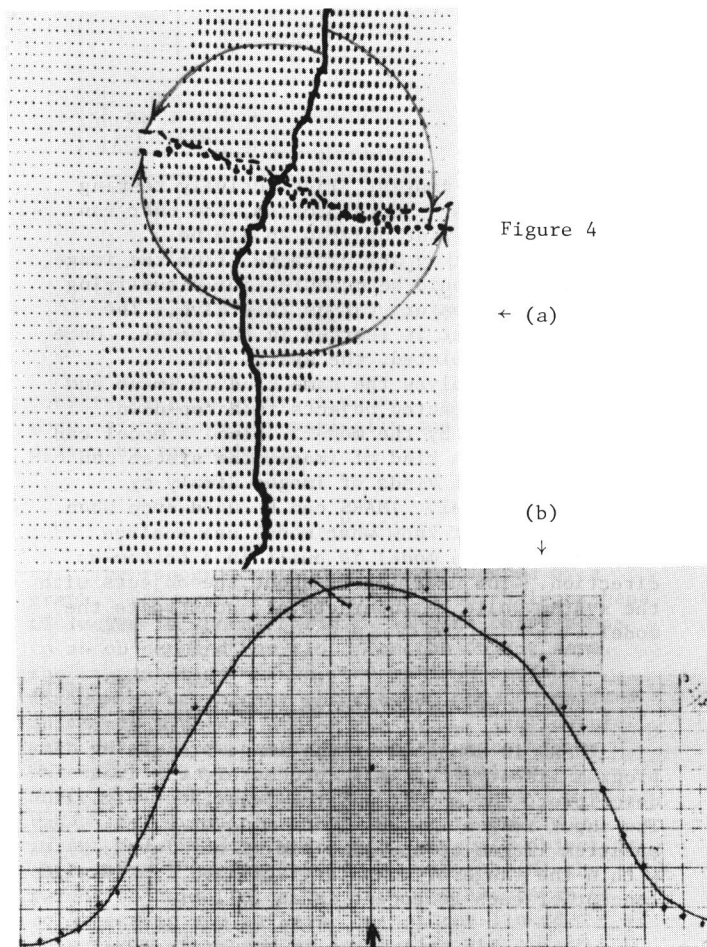


Figure 4

← (a)

(b)  
↓

### III EVALUATION

We apply our model driven enhancement techniques to images obtained by using a clinical DSA unit on animals with coronary artery lesions. The usefulness of the techniques is tested with a Receiver Operating Characteristic (ROC) analysis [11]. The performance of observers in detecting lesions in the original DSA images is compared with their success with the enhanced images and with conventional selective coronary arteriography, considering both increased sensitivity and possible increased false positive diagnosis. The truth or falseness of detected lesions is judged by comparing to specimen angiograms. To increase the number of images for testing, additional synthetic lesions of different size and location are created in the digital images and the ability to detect them with different types of enhancement is studied.

### IV DISCUSSION

We have described work which is currently being pursued as a cooperative project between the Department of Computer and Information Sciences and Department of Radiology at the University of Pennsylvania. The project involves applying techniques of artificial intelligence to solve a significant medical problem. It is our conjecture that the model driven visualization procedures described above will make DSA at least as useful as the more dangerous currently used procedure of selective arteriography. At the time of writing, many of the above-described visualization procedures have been implemented, but the evaluation on the animal model has only just started. Hence validation (or refutation) of our conjecture cannot as yet be given.

### ACKNOWLEDGEMENTS

The authors are grateful to R. Summers, G. Waxler, and M. Wiener for programming help, S. Strommer and P. Porter for the photography, and M.A. Blue for the typing.

### REFERENCES

- [1] DeRouen, T.A., J.A. Murray, and W. Owen, "Variability of the Analysis of Coronary Artery Disease." Am. J. Cardiology 38 (1975) 174-178.
- [2] Brody, W.R. (ed.), Conference on Digital Radiography, Proc. SPIE 314 (1981).
- [3] Brown, B.G., E.L. Bolson, and H.T. Dodge, "Arteriographic Assessment of Coronary Atherosclerosis," Arteriosclerosis 2 (1982) 2-15.
- [4] Ballard, D.H. and C.M. Brown, Computer Vision. Englewood Cliffs, NJ: Prentice-Hall, 1982.
- [5] Bajcsy, R. and M. Tavakoli, "Computer Recognition of Roads from Satellite Pictures," IEEE Trans. Syst. Man. Cyber. 6 (1976) 623-637.
- [6] Udupa, J.K., DISPLAY82 - A System of Programs for the Display of Three-Dimensional Information in CT Data. Medical Image Processing Group Technical Report No. MIPG67. Department of Radiology, Univ. of Pennsylvania (1983).
- [7] Herman, G.T., Image Reconstruction from Projections: The Fundamentals of Computerized Tomography. New York, NY: Academic Press, 1980.
- [8] Broit, C., "Optimal Registration of Deformed Images," Ph.D. Dissertation, University of Pennsylvania, August 1981.
- [9] Deutsch, E.S., "Thinning Algorithms on Rectangular, Hexagonal and Triangular Arrays," Com. ACM 15 (1972) 827-837.
- [10] Freeman, H., "Computer Processing of Line-Drawing Images," Comput. Surv. 6 (1974) 57-97.
- [11] Swets, J.A. and R.M. Pickett, Evaluation of Diagnostic Systems - Methods from Signal Detection Theory. New York, NY: Academic Press, 1982.