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INTERACTIVE 3D DISPLAY OF MEDICAL IMAGES

Stephen M. Pizer, Henry Fuchs,
E. Ralph Heinz, Edward V. Staab, Edward L. Chaney, Julian G. Rosenman,
John D. Austin, Sandra H. Bloomberg, Earle T. MacHardy,
Peter H. Mills, Dorothy C. Strickland
University of North Carolina, Chapel Hill, NC, USA

1. INTRODUCTION

3D display has the potential for increasing the information from medical images that can be used for diagnosis or treatment. It can be accomplished both by displays which present reflections from computed surfaces and by translucent, projective displays. Taking into account both types of display, this paper will

(1) discuss the strengths and weaknesses of 3D display and indicate areas of medical imaging where it seems that these strengths can be capitalized upon.

(2) survey the kinds of preprocessing necessary to prepare an image for 3D display from a series of 2D grey-scale slice images.

(3) present types of interaction and display features that are important as part of 3D display, in particular for projective, translucent 3D display.

(4) summarize the features of system software at UNC that supports the required interaction and display on a particular projective 3D display, a varifocal mirror system designed as an add-on to a color raster graphics system [Fuchs, Pizer, et al, 1982a,b].

We will focus on the varifocal mirror display, but also discuss shaded graphics display. Figures showing the results of shaded graphics reflective surface display will be included, as will stereo pairs taken by photographing the results of projective display by the varifocal mirror from two different angles. Of course, none of these images will be able to capture the effectiveness of interactive display or of the true 3D effect that the varifocal mirror provides.

2. STRENGTHS AND WEAKNESSES OF 3D DISPLAY

As compared to information from a pile of grey-scale slice images, 3D display seems to have a major strength where the comprehension of global 3D structure is important but seems not to be helpful where local issues are the major concern, even if these local issues must be addressed in many of the original image slices. The comprehension of the amount of plaque on the carotid artery wall and the degree of ulceration of the plaque is a local matter, and we have found that in this case 3D display adds little to the information that can be comprehended from grey-scale CT slices from which the 3D display derives.

On the other hand, we have found frequently that radiologists are not able to comprehend 3D structure from the 2D grey-scale slices. For example, we have made 3D images showing artery structure and the relation of clot or plaque to artery (figures 1-3) which allow the viewer to view aspects of global artery structure that are not apparent from the original images. For situations in which such comprehension is diagnostically important, 3D display should be helpful. In particular, such comprehension seems important in cases where

(1) the 3D structure is itself the basic goal, as when directing a surgeon. Others [Herman, Vannier] have commonly found 3D display important for this purpose in surface displays of bone surfaces.

(2) the extent of a complex object is the goal, as when one wishes to measure volume or shape. Examples are in measuring heart chamber volume or wall shape or tumor size. We have seen this to be the case in appreciating the extent of a brain tumor.

(3) appreciation of grey scale variations is the goal but the structure is very complex, so the 3D display can provide a guide for the selection of possibly oblique slices which can then be appreciated as 2D grey-scale images. Harris [1982] reports this to be frequently the case in images of the heart and major vessels.

(4) appreciation of the match between two 3D objects, and possibly the modification of one of these to improve the match. An example with which we have pilot experience is in matching radiation dose to anatomy in radiotherapy treatment planning.

We have seen numerous clinical studies of various organs for which an array of grey-scale slices is not adequate for even an experienced radiologist to comprehend 3D structure. On the other hand, with other than organs with the sharpest, high-contrast edges the 3D display is not adequate without also having the grey-scale slices, because no 3D display modality can portray subtle, spatially complicated grey-scale variations nearly as effectively as 2D grey-scale images. With the varifocal mirror the reason is the obscuration produced on all projective, translucent displays and the limited dynamic range of the phosphor light output for phosphors with the quick quenching time required by the varifocal mirror display principle. With shaded graphics the reason is that display is based on the portrayal of a surface, whose position either is or is not at a particular location but cannot be to different extents there in various locations. To overcome the inability of 3D displays to show needed grey scale information, we conclude that a display system combining 2D and 3D capabilities is required. Pilot studies support this conclusion.

Furthermore, interaction is most important with 3D display. It is important both to aid visualization of the 3D objects being displayed and to allow convenient manipulation and measurement of the objects in the image. Visualization is aided by providing a view from the appropriate orientation, by the kinetic depth effect, and by removal of obscuration by dimming or removal of objects or regions not presently of interest. Manipulation and measurement is provided by allowing translation and rotation of image objects including cursors and by providing a means of specifying irregular volumes of interest. Both of these interactive objectives are severely compromised if response is not provided in a fraction of a second. Motion-related perception of 3D is distinctly lessened and poor feedback harms interactive control. Ways of providing responsive interaction are discussed in section 4 below.

3. PREPROCESSING FOR 3D DISPLAY

Preprocessing for varifocal mirror display has three major objectives: 1) transformation of the image data from a 3D array of intensities in which it normally arrives as a pile of slices to the format required by the varifocal mirror display system, 2) accomplishment of contrast-enhancing and edge strength transformations that improve the perceptibility of image features on the 3D display, and 3) selection of regions or image objects that one wishes to have the option of displaying separately on the 3D display. The first step simply involves transformation of the original pixels into the form of a set of (x,y,z,i) 4-tuples, where i is intensity. Among the options in accomplishing this transformation are scaling and interpolation. While interpolation in all three dimensions is often desirable to remove pixel artifacts, the most important is that in the depth (z) dimension, since without this the view from the side shows the slices from which the image was produced, severely limiting any other perception. We have found that slice artifacts are largely removed if as few as two pixel values are interpolated between each pair of pixels in the same (x,y) positions on adjacent slices, interpolating not at fixed depths between the slices but rather at random depths (different for each pixel pair) uniformly distributed between the slices. It seems that this idea can usefully be extended to interpolation in the x and y dimensions.

As will be explained in section 4, it is useful to randomly shuffle the resulting 3D points before they are used to define objects for 3D display.

A major advantage of varifocal mirror display over shaded graphics display is that it can be used as an exploratory modalilty. Shaded graphics' strength seems to be as a means of showing someone 3D views of objects that have already been perceived as objects, though not necessarily in 3D, for example in guiding surgeons. Especially with the noisy, blurred, low contrast objects in medical images, this perception requires human involvement in defining the object surfaces that shaded graphics requires. On the other hand, if a display is to be used to explore images for the information they contain, only automatic preprocessing involving little or no loss of image information should be used. The major objectives of this preprocessing is contrast enhancement and limiting the obscuration that all projective, translucent, true 3D displays produce when one object is in front of or behind another.

The most effective contrast enhancement method for 2D medical images that we know of is our method of adaptive histogram equalization [Pizer, 1981, 1983]. We have sometimes used it with good effect in 3D varifocal mirror display, but there it has two major weaknesses. The first is that it enhances contrast which is not of interest as well as that which is. In 2D this is no problem, but in 3D the uninteresting objects can obscure the interesting ones. The second weakness is that it destroys the intensity ordering relationships within the image, so that windowing can no longer be used to pick out objects of interest and remove others from obscuring the objects of interest. As a result we recommend global histogram equalization, with the histogram coming only from the range of intensities in the body (see figure 4) or a smaller range selectable based on the organ system of interest. After this transformation, the image objects become far more apparent than if no contrast enhancement were done, and also intensity windowing, as described in section 3, can be applied to reduce obscuration.

Obscuration is also lessened by displaying edge strength to show surfaces rather than the original or contrast-enhanced grey-scale values, which result in the inside of objects obscuring their surfaces. Edge strength transformations, such as that due to Sobel and its 3D extension, both of which are used by us (see figure 5), are effective only after appropriate contrast enhancement. The same contrast enhancements discussed in the previous paragraph are applicable, except that adaptive histogram equalization can indeed be attractive for this application. Edge strength display is often very effective, since it allows the viewer to put points in the contrast-enhanced image with a high intensity gradient to be coalesced into a surface by the viewer while allowing him to ignore the scattered non-surface high-gradient points that come from image noise. However, when the noise level in one part of the image is comparable to edge intensity difference in another, the high-gradient points due to noise can swamp the image and no windowing can remove the noise points without also removing important object edge points. This high relative noise can occur when adaptive histogram equalization is used in a image where noise appears in a region with a low contrast range and is thus enhanced by the processing. In this kind of a situation a global contrast enhancement that is not locally adaptive such as the range-limited histogram equalization method described above should precede edge strength measurement. Alternatively, the image can be pre-smoothed by a method that preserves edges (see figure 5), such as one we have developed based on accepting pixels into a local average only if they are appropriately close in intensity to that of the pixel whose smoothed value is being computed [Austin, 1982].

Object or region specification can also be important as a step towards limiting obscuration by allowing the objects or regions thus defined to be selected among or displayed using differing relative intensities or display modes such as color or blink. The specification to which we refer is of regions which are not simply a range in each of x, y, and z, as can be defined in real time on line by the display device, as described in section 4. Ideally the specification of general objects or regions should be done based on simultaneous 2D and 3D display, as discussed in section 2. However, at present we have developed a program for specifying objects using a sequence of slices, displayed as an array of 2D images. In this program the user specifies a closed contour on one slice, and the program determines the corresponding contour on succeeding slices, using edge strength and direction values computed for these slices (see figure 6). The user can edit contours where the edge that is found is in some part not the one desired, and then the edited edge forms the basis for the edge on the next slice.

The method for finding a contour on one slice given a prototype contour on the previous slice and the edge strength and direction values on the new slice is based on the Hough Transform [Ballard & Brown, 1982]. The contour on each slice is represented as a cyclic series of points connected by line segments. Each point on one slice is replaced by another on the next slice by fitting the line segments connecting the points to the edge information in the new slice. For each line segment in the prototype, a rectangular box is centered about the line (see figure 7). The width of the box is a parameter of the program specifying the distance from the prototype to search for the new edge. All pixels in the box whose edge strength is above a given threshold are given votes as to the identity of the new line segment. Each such pixel votes most strongly for the line through it with its edge direction value, and less strongly for lines with nearby slopes and intercepts. The line segment chosen is the one with the most votes, if this number of votes is above some threshold. If not, the prototype segment is used.

The new edge points are determined by intersecting the new line segments. For a pair of line segments sharing a point in the prototype, the intersection of the new line segments with the ends of their boxes near the point are each calculated, as well as the intersection of the two line segments. If this intersection of the lines is near enough to the box intersections, the intersection of the lines is used as the new point. If not, the new point is a weighted average of the two box intersections, with the weights being the number of votes received by the respective line segments.

The success of the object specification method just described depends on the contrast of the edges in the underlying image and on separation of edges relative to the distance moved by an edge from slice to slice. The edges thus produced can be used as the basis of a region definition for varifocal mirror display by selecting an annulus about the edge, the region inside the edge, the region outside the edge, or some union of these,. In this case the edge need not be exact. It is also possible to use these results to define contours for tiling and subsequent shaded graphics display (see figure 8), but the accuracy requirements there are much more stringent.

The preprocessing necessary for varifocal mirror and shaded graphics display is summarized in figure 9.

4. INTERACTION AND DISPLAY FEATURES FOR VARIFOCAL MIRROR 3D DISPLAY

For visualization it is important for a projective, translucent 3D display to provide the ability to select among objects, to allow, for each object, selection of orientation, relative intensity, and other intensity properties such as blink, and to allow spatial and intensity windowing. For manipulation of image objects it is also important to allow object translation, pointing, region specification, and plane selection to indicate slices of interest that can be displayed on the 2D display component of the display system that presents grey-scale information most effectively. In the following we describe how our raster-graphics-system based varifocal mirror display system described in Fuchs and Pizer [1982a,b] provides these capabilities.

The object descriptions produced by the preprocessing each consist of a set of (x,y,z,i) 4-tuples. Each object needs to be rotated and translated and have its intensities transformed to a set of (x',y',z',i') 4-tuples. This is accomplished by the display processor in the raster graphics system on which our varifocal mirror display system is based, using standard graphics techniques. Then as described in Fuchs and Pizer [1982a], each z' is used to select a depth bucket of the refresh buffer, into whose first free location the corresponding (x',y',i') is placed. More precisely, the triple (x',y',0), i.e. the new location but with zero intensity followed by the triple (x',y',i') is placed into the refresh buffer. The first triple is required to allow the CRT beam to move to (x',y') without leaving a trail or a smear before the beam is appropriately intensified.

In order to allow the viewer to receive immediate feedback from his interaction we wish to display whatever points have been transformed into the refresh buffer after 1/30 sec. Because the object descriptions have their points in random order, a full but coarse coverage of the object will provided by this initial display. If at that time further modification of the interactive parameters has been done, a new refresh buffer will be computed based on the new transformation. However, if the user has not changed the orientation, translation, or other interactive parameter, the processor can continue filling the original refresh buffer with further points from the object descriptions. We call this approach successive refinement, and have found it quite successful. Furthermore, after the refresh buffer or one of its depth buckets becomes full, one can make space for additional points from the object description to be transformed by reordering the points so that almost all successive points in a depth bucket are near enough in (x',y') so that little CRT beam movement is required and thus intervening zero-intensity points need be inserted only where the nearness required cannot be achieved.

Pointing is achieved by having an object describing a cursor and logically attaching it to an interactive device. Region specification can be accomplished by painting using such a cursor and creating a new object description on the fly from the region that is painted or its surface (computing this surface quickly is a problem yet to be solved). Alternatively the cursor can be used as an eraser by recording the region painted and not loading into the refresh buffer any point whose transformed value is in the erased region.

Spatial and intensity windowing, which are global to the whole image, can be accomplished in real time using the color lookup tables and viewport registers of the raster graphics system. Since the x,y,i values in the refresh buffers are stored in the frame buffer in the locations used for red, green, and blue for color video display, the red and green lookup tables can be used to do windowing in the x and y directions, respectively, on the varifocal mirror. All table entries for x (or y) values less than an interactively specified minimum and greater than an interactively specified maximum are set to zero, with the result that all such points appear at an edge of the picture. Similarly, intensity windowing can be done by loading an appropriate blue lookup table. Note that on the varifocal mirror intensities above as well as below the window should be mapped to zero intensity to avoid obscuration.

Depth windowing is more important than x and y spatial windowing, since it relieves more obscuration. Here we take advantage of the fact that distance along the frame buffer, i.e. successive lines when the buffer is used for video display, correspond to successive levels of depth on the varifocal mirror display. Thus, restricting display to a certain range of video lines is equivalent on the varifocal mirror to restricting display to a certain range of depths. This is just the function of the video-y viewport registers in many raster graphics systems. Thus, settings of interactive controls determining a desired depth window are used to load the video-y viewport registers and thus restrict display to the desired depth window.

A factor worthy of discussion is the number of points required for 3D varifocal mirror display. Because obscuration needs to be avoided, it is frequently the case that the number of points desired is proportional to the square of the number of points in a linear dimension rather than the cube. This limitation is acheived, for example, by the edge strength transformation followed by accepting points above some edge strength threshold, or spatial or intensity windowing. Our experience indicates that a 256 x 256 x 64 depth bucket x 16 intensity system is adequate and a 512 x 512 x 128 x 32 system can be justified. Furthermore 32K points is clearly inadequate and 64K is still not enough. Based on our experience with our system and that of others, we suspect that perhaps 200,000 points will be satisfactory to display multiple objects, each with appropriate point density.

These numbers can be used to compare raster-based systems to point-based systems, such as ours. A raster-based system must store only i but do so at many unused points. A point-oriented system must store (x,y,i) for each point. Even at the lower resolution a raster system would require a refresh buffer of 20 million bits, whereas a point-based system would require 4.4 million bits, or 8.8 million if space is allocated so that every point can include a zero intensity entry. Furthermore, many of the interactions are difficult with a raster-based system.

5. SOFTWARE TO SUPPORT VARIFOCAL MIRROR DISPLAY

Varifocal mirror display is simply a graphics display, and the software to support it is no different in principle than that to support other graphics displays, such as vector graphics and raster graphics systems. The only exception is that varifocal mirror software must include software appropriate for the special preprocessing required, and certain of the transformations are specialized to the varifocal mirror display. Thus, the software used after preprocessing consists of programs to transform object descriptions for multiple objects into refresh buffers and software to load the display device registers and tables.

Our varifocal mirror display is implemented as an add-on to an Ikonas RDS-3000 raster graphics system that contains an AMD 2900-based parallel bit-sliced microprocessor as the display processor and also a fast multiply/accumulate chip. Our software operates by loading object descriptions, at user command, into part of the frame buffer. Then interactive devices are logically attached to objects specified by the user, so that transformations specified by the position of the devices are loaded from the host computer to the raster graphics system. These transformations are applied to the appropriate objects via the display processor and multiply/accumulate chip and stored in the refresh buffer.

The refresh buffer is organized by the level of dynamism of the objects, these levels being determined by the user. We normally use two levels, dynamic and static, or three, busily dynamic, dynamic from time to time, and static. The loading of a refresh buffer is done in increasing order of dynamism, while assuring that enough space is left to hold the more dynamic objects. The result is that when a dynamic object is moved, only the part of the buffer at its level of dynamism or above need be erased and refilled, considerably speeding the effect of interactions.

The software we have developed supports both single and double refresh buffers. The successful idea of successive refinement has been extended to using a single buffer (of double the size of a double buffer) if interaction is not occurring after the double buffer is full, and switching back to double buffering when interaction recommences.

6. CONCLUSIONS

Interaction has been seen to be crucial in 3D display of medical images. For exploratory display projective, translucent 3D display seems neccessary. We have therefore developed a varifocal mirror display system that supports interactive use, using a design as an add-on to a raster graphics system that keeps the additional cost of 3D display relatively low. Further developments are needed to make such a display clinically useful, especially in the area of simultaneous 2D and 3D display, interaction based on successive refinement, and improved 3D interactive devices. However, our studies suggest that such a system will be clinically important in areas where global structure properties or relationships are clinically relevant. Finally, we have designs which will allow 3D dynamic display and envision this also being of clinical importance, for example for studying the heart.

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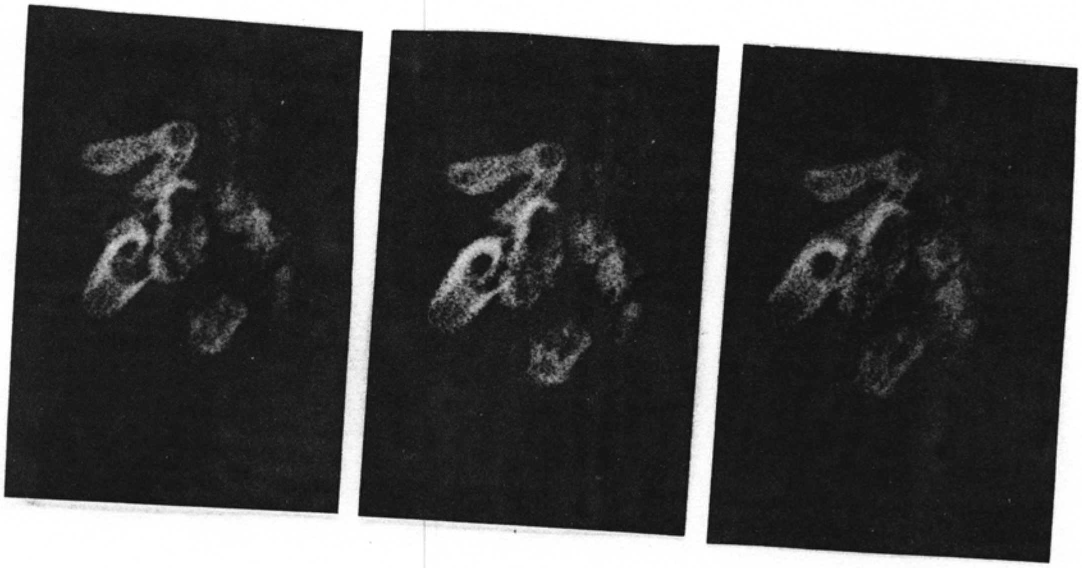


Figure 1
View from three nearby angles of edge strength of blood from CT scan; either adjacent pair may be viewed in stereo. Produced by photographing varifocal mirror.

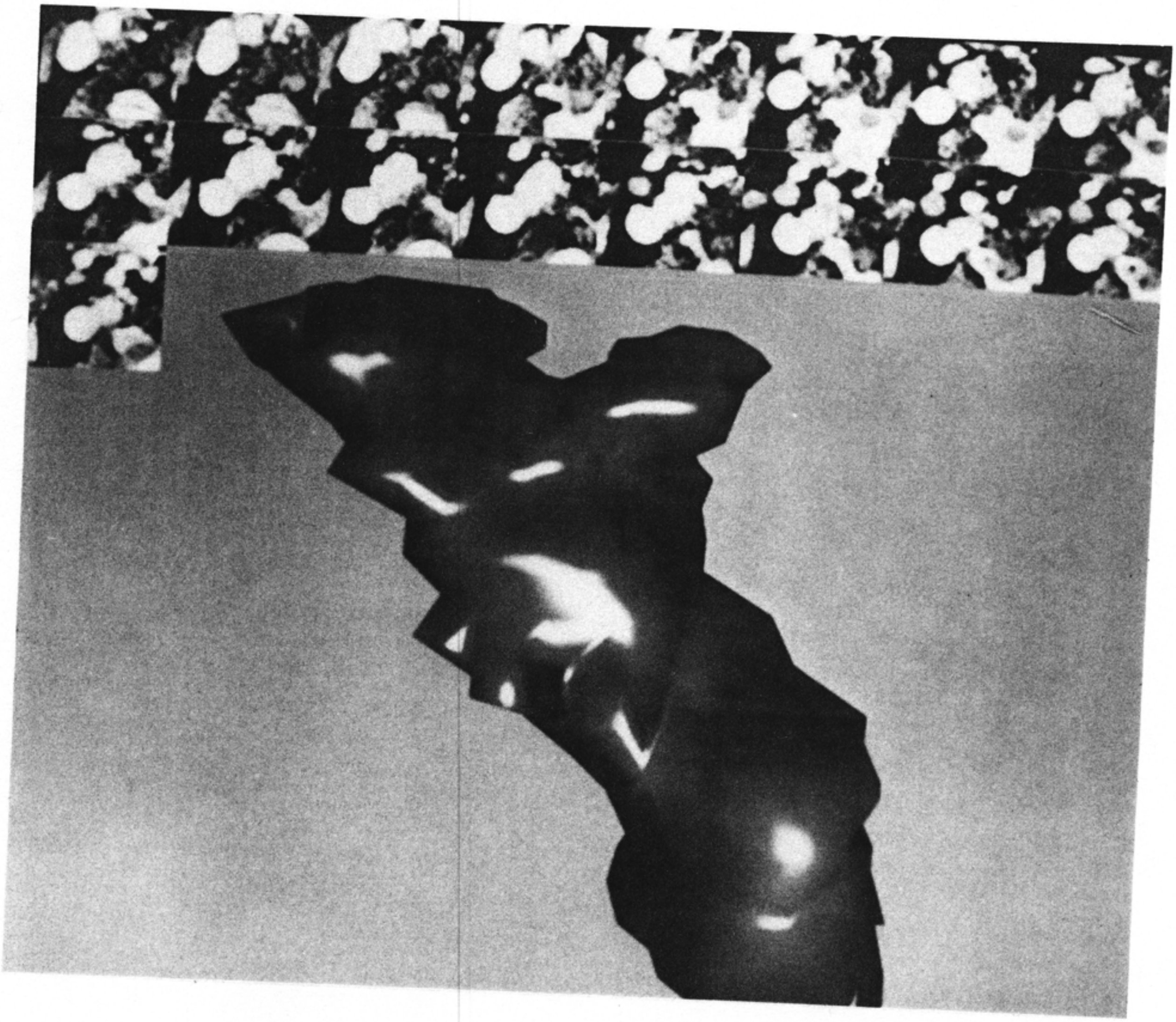


Figure 2
Shaded graphics presentation of carotid artery blood surface from CT scan.
Surface indicates ulcer in plaque on vessel wall.

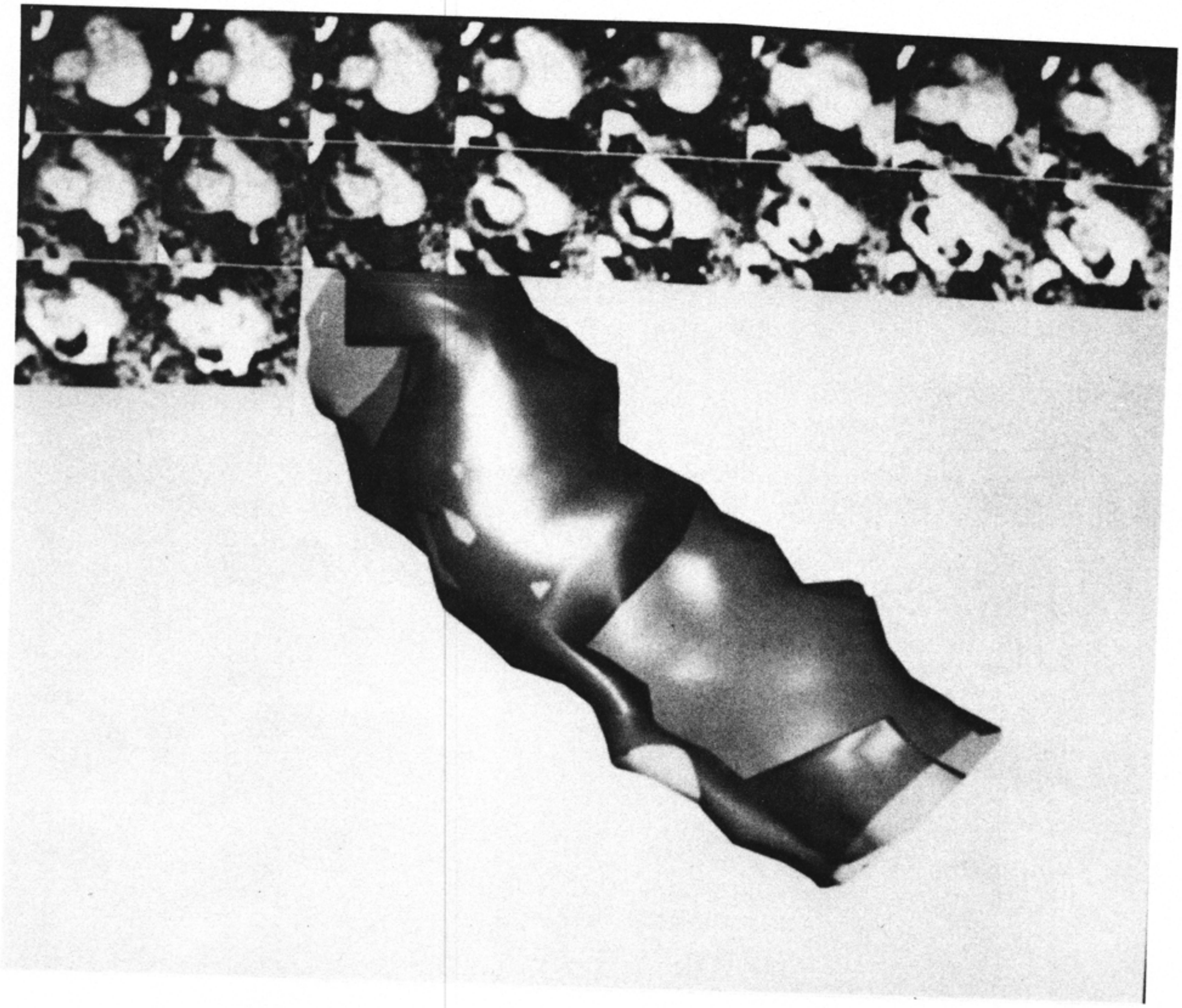


Figure 3
Shaded graphics presentation of clot inside (transparent) carotid artery from CT scans.

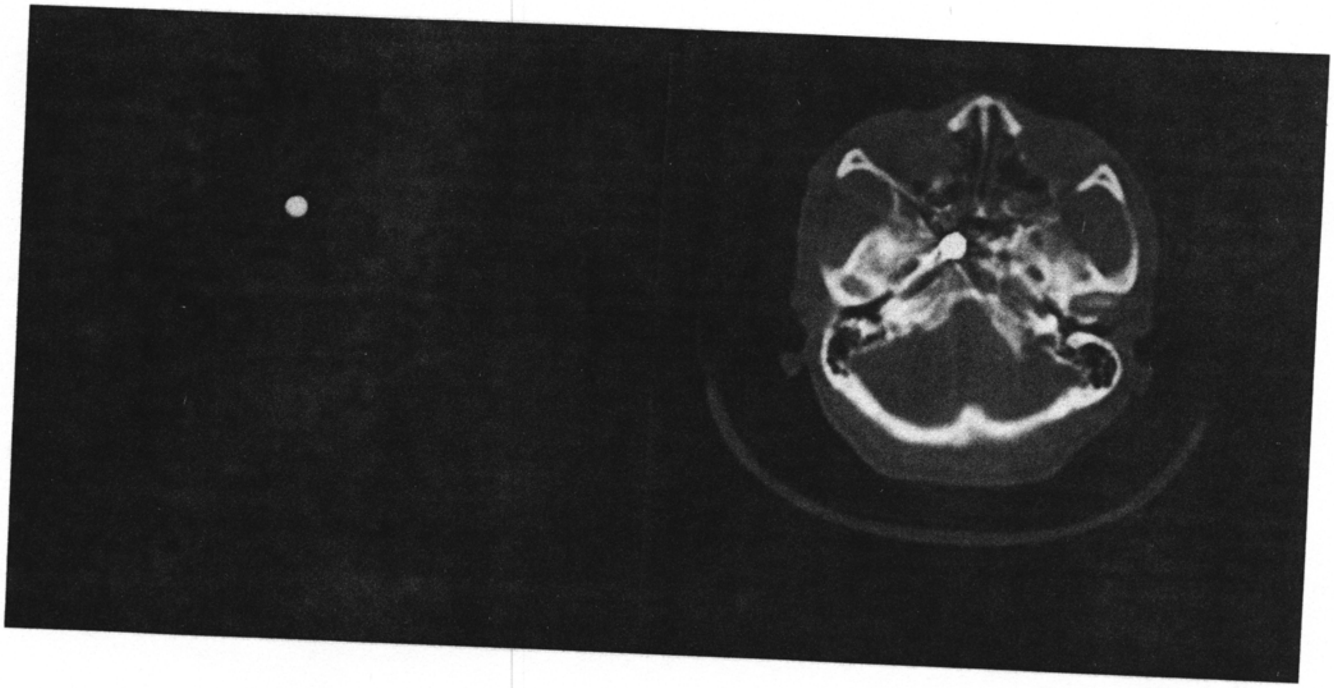


Figure 4

CT scan of bullet in brain

a) before any contrast enhancement

b) after range limited histogram equalization using range of body intensities.

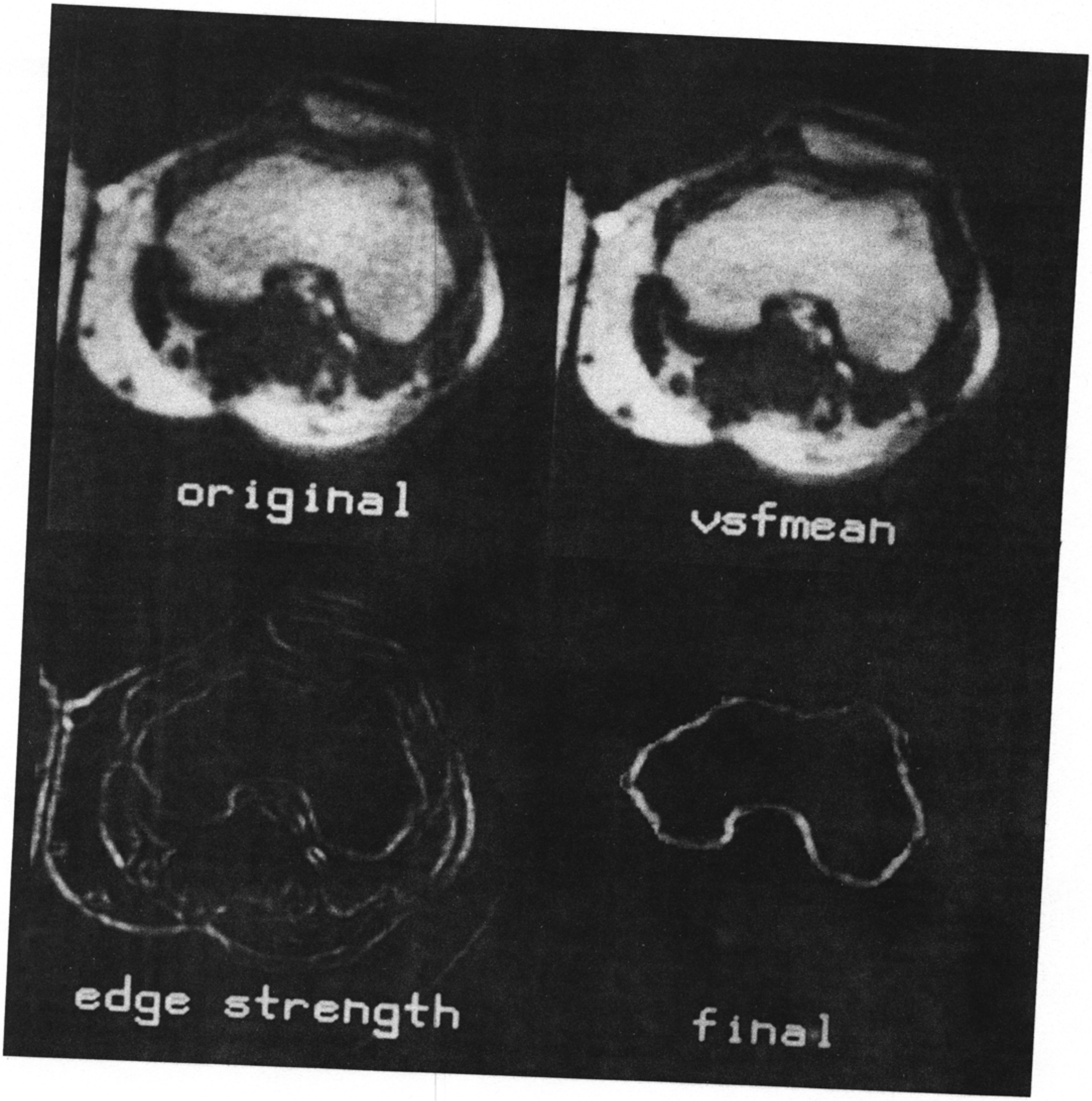
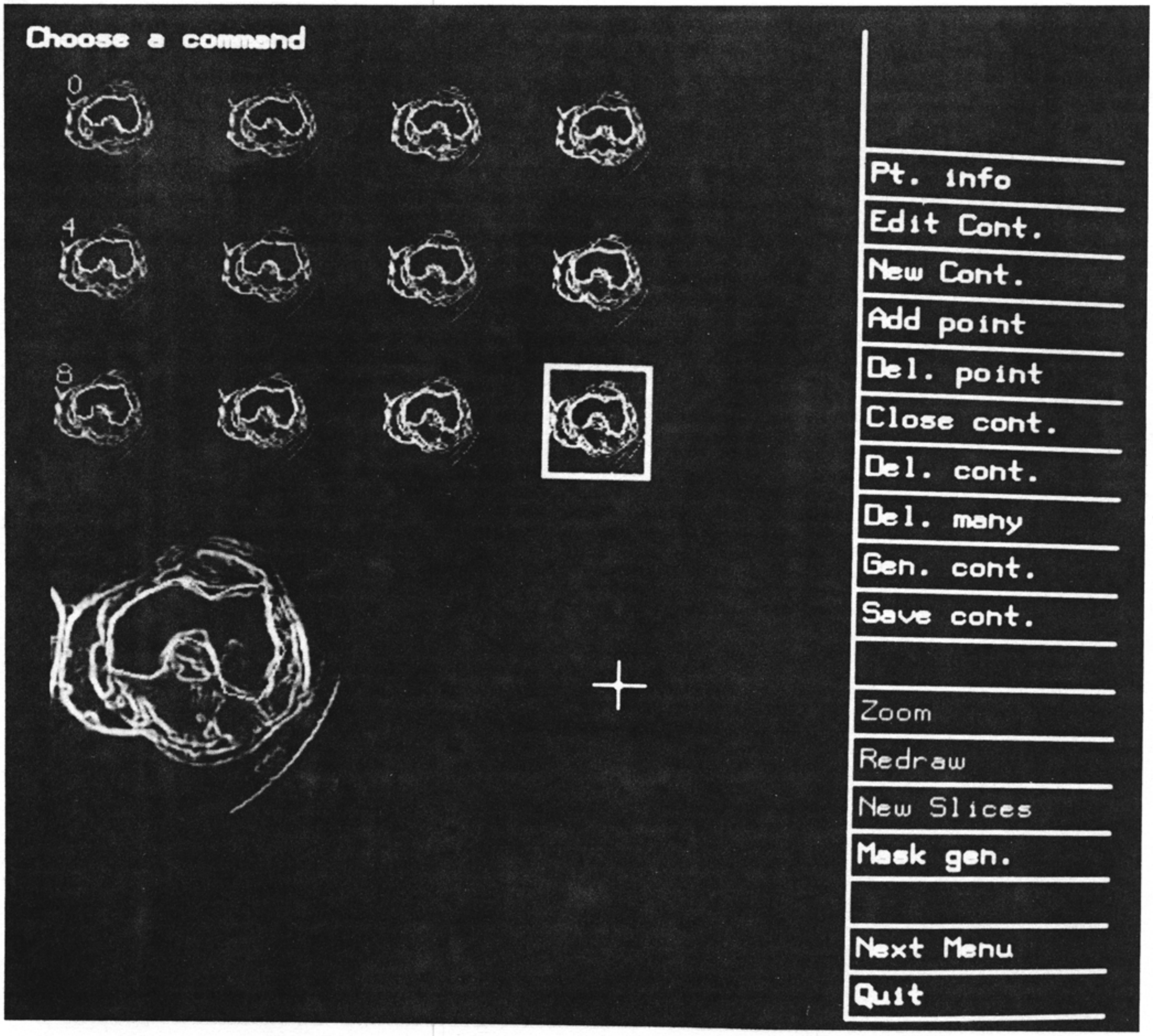


Figure 5

Preprocessing reference for varifocal mirror display of NMR images of the knee.



Choose a command

Figure 6
Result of Hough-transform-based slice-to-slice edge following of femur marrow surface on NMR images of knee.

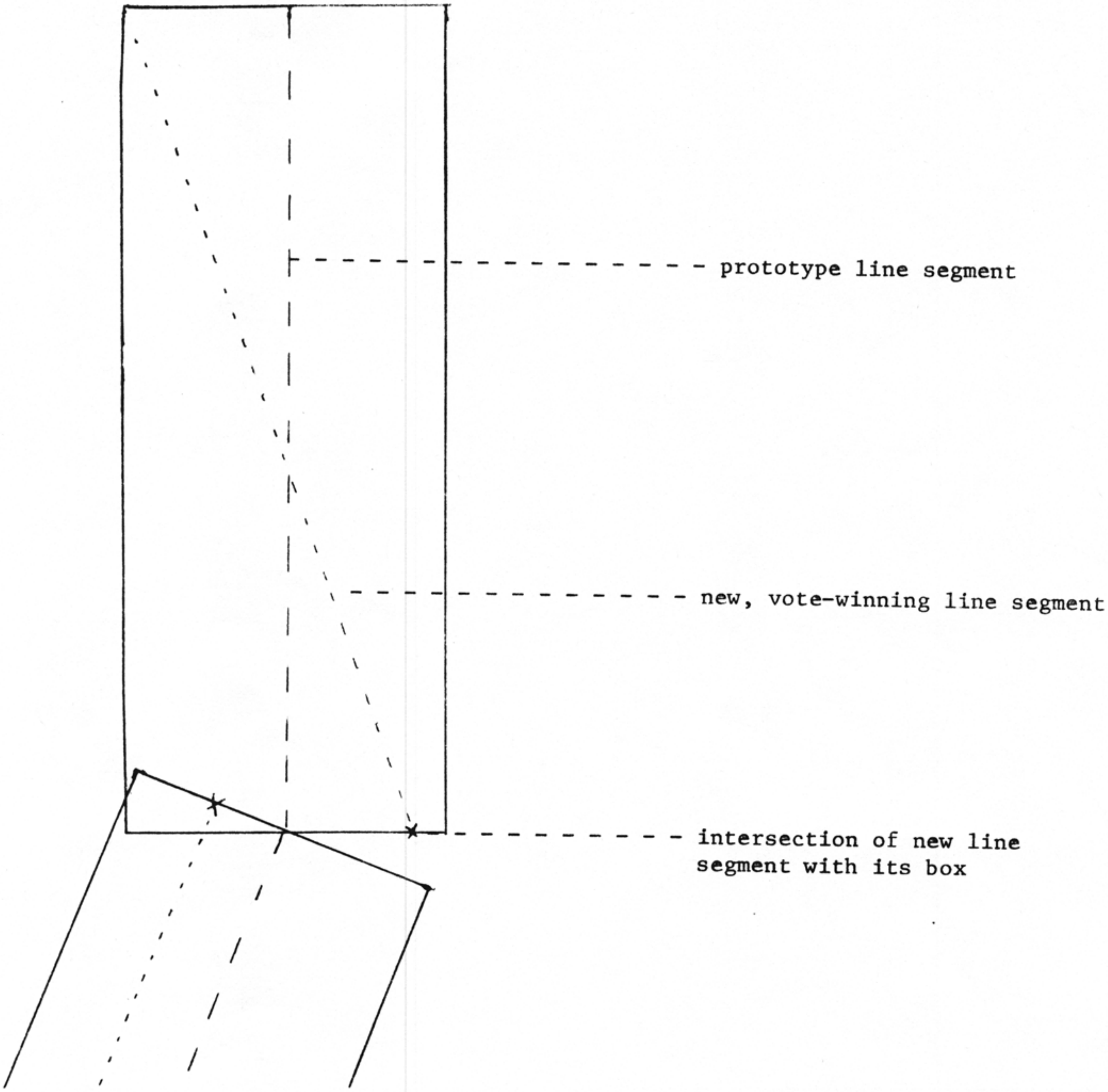


Figure 7
Boxes and linear segments of edges in Hough-transform-based slice-to-slice edge following method.

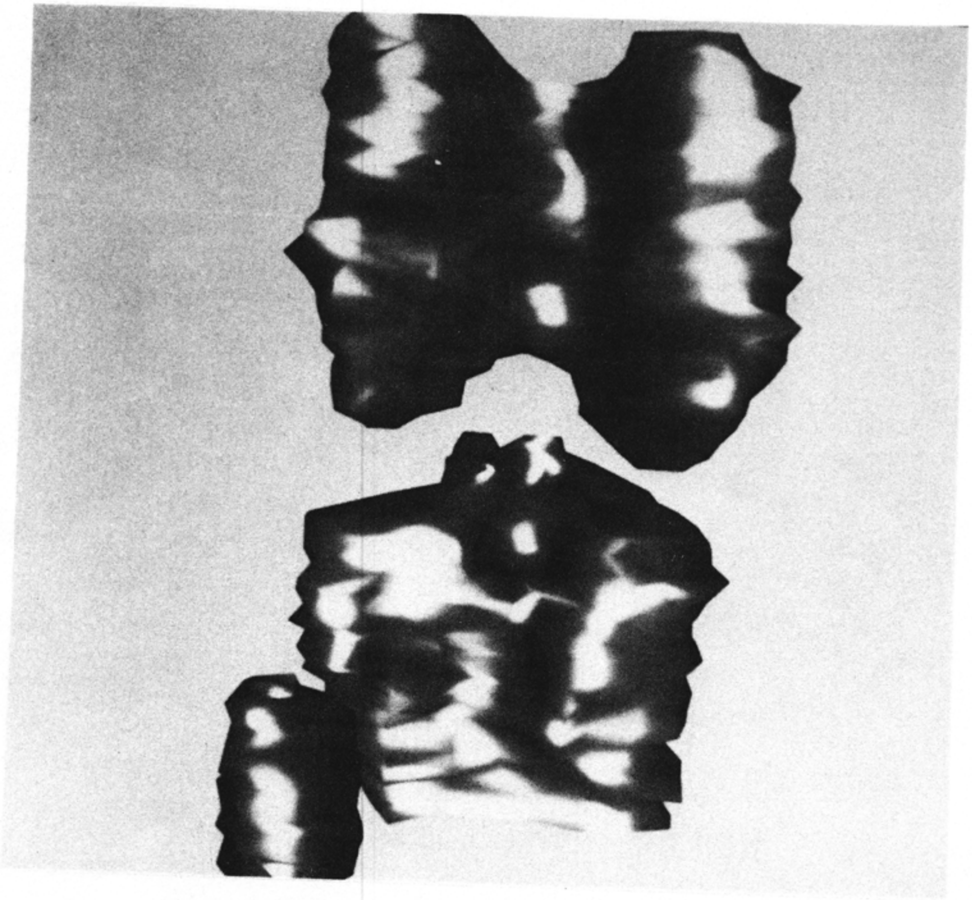


Figure 8
Shaded graphics presentation of tiled contours of marrow surfaces in knee bones from NMR images. Contours produced semi-automatically using Hough-transform-based method.

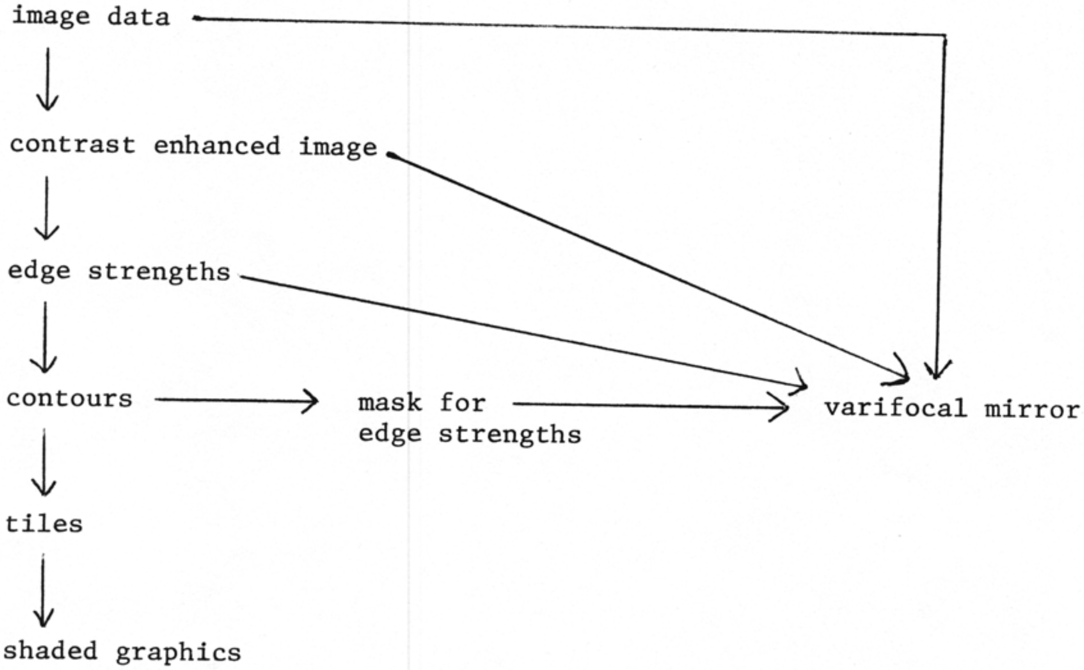


Figure 9
Preprocessing for varifocal mirror and shaded graphics display.

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