Digital Tomosynthesis: Technique for Electronic Reconstructive Tomography

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A technique is described for obtaining tomographic images through retrospective reconstruction of digital data. The apparatus used for this technique, called digital tomosynthesis consists of a linear tomographic x-ray machine that has been modified by the addition of a fluoroscope and TV system, a video disk recorder, an analog-to-digital converter, and a small computer for data processing and manipulation. Video frames are collected and stored during a single tomographic sweep. The stored data are then digitized and retrospectively processed in the computer for reconstruction of any desired tomographic plane within the body. The major advantages of DTS include short patient study time, low radiation dose compared with conventional tomography, the ability to enhance the digitized image through manipulation of window and level display, and the applicability of this technique to dynamic studies such as angiography. Phantom studies show good diagnostic quality of the resulting images, and preliminary vascular studies in dogs indicate the clinical potential of this technique for use in digital subtraction angiography.

On the basis of the pioneering work of Ziedses des Plantes [1] in 1932, Miller et al. [2] published a report in 1971 that described a method for producing an infinite number of planar images from a finite number of radiographs. The technique involved the film recording of multiple radiographs of an object from different angles. By appropriate registration of the radiographs, the different planes within an object could be reproduced and photographed. Although the method was very cumbersome and suffered severe limitations due to the loss of detail and contrast from superimposition of multiple radiographs, these investigators nonetheless demonstrated the feasibility of such a technique.

Subsequently, Baily et al. [3-5] described an electronic system capable of displaying different tomographic planes using the same principles described by Miller et al. [2]. They obtained tomographic images using an image intensifier and TV camera and displayed these images on an electronic storage tube. By altering the shape and position of the TV raster for each successive TV frame, different planes within an object could be displayed.

During the past 2 years we have assembled a digital image processing system at The University of Texas Health Science Center at Dallas that is capable of synthesizing tomographic images of any plane parallel to tube movement within an object. Through digitization of the video images and computer-assisted reconstruction of tomographic images, this system improves the signal-to-noise ratio of the resulting pictures, limits distortion, and vastly improves capabilities for image enhancement and manipulation. The system design provides the capability for applying this technique to dynamic studies such as angiography. Other applications of digital fluoroscopy such as intravenous digital angiography can also be used in conjunction with the digital tomosynthesis (DTS) technique [6].
Equipment and Principles

The system consists of a conventional x-ray machine with linear tomographic capabilities to which is affixed a nine inch (22.9 cm) image intensifier and TV system. The TV chain is attached to an Eigen analog video disk recorder with a 6 MHz band width and a 50 db signal-to-noise ratio. This disk is capable of operating in real time with recording or playback at rates up to 30 frames/sec. A Quantex DS-30 analog-to-digital converter (ADC) with a 512 × 512 video memory matrix is used to digitize the images at an eight bit depth providing 256 gray levels. A small computer is used to control the ADC and to rearrange data within the digital video memory for display on the TV monitor. A schematic representation of the operating system is shown in figure 1.

The general principles by which the system operates can best be understood by first considering how a tomographic picture is formed. Any given point on the fulcrum plane of a tomographic section is projected in a constant position on the input screen of the image intensifier during the entire tomographic sweep. That point is thus recorded as a sharp image on the resulting tomographic picture. Points that lie in a plane other than the fulcrum plane move at different rates and are projected at different positions during the sweep of the image intensifier. These points are blurred on the final image. The speed at which a point moves across the face of the image intensifier screen varies directly with its distance from the fulcrum plane. Thus, points that lie close to the fulcrum plane will move more slowly with respect to the image intensifier than points that lie further from the focal plane.

If a tomographic image is obtained fluoroscopically, that image can be considered to be composed of a finite number of individual TV frames exposed at equally spaced intervals during the tomographic motion. By digitizing and storing each individual TV frame and using the principles described above (i.e., that points on different planes within the body move at different speeds with respect to the image intensifier), any plane parallel to tube motion within an object may be reconstructed through computer processing of the individual digitized frames.

This is illustrated graphically by considering a very simple system consisting of an x-ray tube, a portion of a digital video matrix, and two points labeled A and B that lie, respectively, on the fulcrum plane (0 plane) of the tomographic image and at some arbitrary distance off the fulcrum plane (fig. 2A).

By selecting three positions or frames along the tomographic sweep (fig. 2B), it can be seen that in each of the three frames, point A, which lies on the fulcrum plane, is projected on the same central pixel of the digital matrix.
Point B, on the other hand, is projected at three different pixel positions on each of the three successive images. If the individual frames are summed (fig. 2C), the result is a composite picture in which point A maintains a constant position and is thus projected as a sharp image, while point B lies in different positions within the matrix and is thus blurred across the image.

Now if the alignment of the individual pixels within each digitized TV frame is shifted so that all the pixels containing point B lie at the same position and the shifted matrices are summed, the resulting image shows point B projected within the same pixel element as a sharp image and point A is projected within different pixel elements and thus blurred across the image (fig. 2D).

In actual practice, the raw data consisting of the individual TV frames from the tomographic sweep are acquired and stored on the analog disk recorder. The images are post-processed by digitizing each individual frame in the ADC. The plane to be viewed is determined and the proper position for each digitized frame is calculated, aligned at the appropriate position within the digital video matrix, and summed to the preceding frames by the computer.

**Results**

The curved input face of the image intensifier actually produces a curved "fulcrum-plane" cut and can lead to image degradation at the periphery of other planes. Computer processing during reconstruction can eliminate the degradation. Initial tests of the system were made using various plastic and wire mesh phantoms. Considerations concerning possible field inhomogeneities or distortion of images from the curved input surface of the image intensifier were evaluated and were found not to be serious limitations. Feasibility studies were then designed to answer several specific questions. Does the technique produce true tomographic images in different parallel planes that are of good quality? How do the tomosynthesis images compare with actual tomographic images of the same plane? Will the system work in such a manner as to make it a potentially usable clinical tool?

Linear tomographic studies were performed using a skull phantom embedded in Lucite. The phantom was first tomographed using the full nine inch (22.9 cm) field of the image intensifier. For purposes of this discussion, the fulcrum plane of the tomographic sweep from which the raw data images are collected will be referred to as the zero (0) plane. The tomosynthesis pictures are defined in reference to the 0 plane as some distance in front or in back of this plane.

In the first series of studies (fig. 3), the 0-plane image of the skull lies at the plane of the internal auditory canals. Good detail of the petrous bones is demonstrated along with parts of the hypoglossal canals and the anterior margin of the foramen magnum. To determine the anatomic detail demonstrated by a relatively large shift of the tomosynthesis plane, a section 6 cm anterior to the 0 plane was reconstructed. This section passes through the orbits, maxillary sinuses, nasal septum, and hard palate. Sharp, accurate detail of these anatomic structures is seen in the DTS image. To evaluate the quality of the computer-reconstructed DTS pictures, a DTS image and an actual tomographic image were made at about the same level and compared (fig. 4). Comparison between the tomosynthesized image (fig. 4A) and the actual tomogram (fig. 4B) shows excellent detail and accuracy of the computer-generated image.

The next question to be answered was whether the system would be capable of separating finely detailed structures that lie in planes very close together. Using the five-inch (12.7 cm) fluoroscopic field of the image intensifier, a section was taken with the 0 plane again passing through the internal auditory canal (fig. 5A). A tomosynthesis plane 4 mm anterior to 0 was reconstructed that clearly shows the spiral turns of the cochlea (fig. 5B). These images are even more remarkable when one considers that this detail was obtained using linear tomographic techniques rather than hypocycloidal or trispiral techniques.

One of the major advantages of digital radiographic systems in general is the ability to manipulate the image display to enhance areas of interest in a manner analogous to the window and level controls on a CT scanner. This capability is also applicable to the DTS image and is illustrated in figure 6. Display of the entire range of gray-scale values in figure 6A results in a flat image with poor contrast, which is reminiscent of conventional film-screen tomographic images, while window and level manipulation of the gray-scale display in figure 6B enhances the cortical margins of the otic capsule, resulting in better definition of the spiral turns of the cochlea.

Since the DTS technique enables images of any parallel plane within the body to be synthesized from data obtained during a single tomographic sweep, the potential for dy-
namic imaging at multiple levels becomes a real possibility. A major area of potential clinical application for this technique is angiotomography. In order to test the feasibility of DTS in angiotomography, we performed initial studies on dogs.

Mongrel dogs weighing 20–25 kg were anesthetized and a catheter was inserted through the femoral artery and advanced into the ascending aortic arch. Contrast material (Conray-60; 10ml/sec for 2 sec) was injected into the arch to simultaneously opacify all of the cerebral vessels, and DTS images of the head were obtained.

Figure 7 shows the comparison of DTS images reconstructed at three different planes of the head. The 0 plane is obtained through the left paramedian area, at which level the left maxillary artery can be seen at the base of the skull. A tomosynthesis section about 1 cm to the right of the 0 plane now defines a plane of section in the midline with visualization of the basilar artery, the anterior cerebral artery, and the pericallosal artery. A tomosynthesis section 4 cm to the right of the 0 plane now defines a plane on the right side of the head, which shows the right maxillary artery at the base of the skull and the right superficial temporal artery. The morphology of the different vascular structures is clearly shown in these images and indicates that the DTS images are indeed focusing on selected individual vessels within the head. Many of these are small vessels with internal luminal diameters of less than 1 mm.

Visualization of these tiny intracranial vessels can be dramatically improved through the use of subtraction techniques and manipulation of the digital display windows. This is feasible also with DTS by first collecting data from a tomographic sweep before the injection of contrast material and using this data to synthesize a mask image. Similar tomosynthesis planes are then reconstructed from the mask data and from the contrast data, and these are subtracted and enhanced. The results of this method can be seen in figure 8, which illustrates the same three images shown in figure 7 after subtraction and enhancement. The results of these studies show the tremendous potential of DTS techniques for use in digital subtraction angiography.

Discussion
The application of computer-assisted digital image processing to radiographic studies of all kinds is rapidly ex-
Fig. 6.—DTS image enhancement by digital selection. A, Full range of gray scale is displayed and resulting image shows poor contrast and poor detail of otic capsule. This image is reminiscent of conventional film-screen tomographic images. B, Same image after window and level manipulation to optimize definition of cortical bone margins. Markedly improved definition of spiral turns of cochlea.

Fig. 7.—DTS images of canine cranial arteries after 20 ml injection of contrast material into aortic arch. A, 0 plane image lies to left of midsagittal plane. Part of left maxillary artery (arrow) is shown together with multiple intracranial arterial branches. B, DTS image reconstructed 1 cm to the right of 0 now defines midsagittal plane. Basilar artery (arrowheads) and pericallosal arteries (arrows) are well shown. C, Computer-generated image reconstructed 4 cm to the right of 0 now shows right maxillary artery (long arrow) and superficial temporal artery on right side (short arrows).

Fig. 8.—Digital subtraction angiographic images corresponding to fig. 7 after subtraction and enhancement of image through window and level manipulation. A, 0 plane centered in left paramedian region. B, Computer-generated image reconstructed 1 cm to the right of 0 defines midsagittal plane. C, DTS image reconstructed 4 cm to the right of 0 plane.
Some authorities predict replacement of x-ray film with totally electronic digital radiographic systems within the next several years. Even with the current refinement of computed tomography (CT) there remains a need for conventional tomographic techniques in most radiology departments [7, 8]. CT scanners are expensive and very busy machines, and conventional tomography can frequently answer a question quickly or screen for large abnormalities such as pulmonary nodules. It can remove bowel gas shadows, which may obscure kidney outlines during excretory urography, and define critical bony relationships in fractures of the spine.

Our application of digital image processing techniques for tomographic imaging provides several advantages over conventional tomographic techniques. The DTS technique has the advantage of a rapid patient study time since the data can be collected in a matter of seconds during one tomographic sweep and then retrospectively reassembled to synthesize multiple tomographic planes even after the patient has left the radiology department. With the use of appropriate computer hardware and software, the actual computer reconstruction time can be extremely rapid, well under 1 min reconstruction time/picture, although with our early prototype equipment it takes several minutes to reconstruct one picture. In addition, the tomosynthesis technique has a much lower radiation dose by virtue of two important factors: first, the images are obtained using fluoroscopic exposure rates rather than the higher dose rates used with a film-screen combination; and second, only one tomographic sweep is made for each set of images. Since many tomographic studies may require as many as 10–20 sections/view, it can be seen that DTS may reduce exposure to the patient by a very large factor.

The most important and exciting potential application of this technique is in dynamic tomographic studies. Angiography is a technique that has been used in many clinical departments including our own, but the conventional angio­tomogram is generally limited to only one plane of visualization. If either the wrong tomographic plane is selected or if one desires to study more than one plane, additional filming runs are required, resulting in increased contrast volume, increased radiation exposure, increased risk to the patient, and increased procedure time and cost. With the DTS technique, data acquired from a single angiotomographic sequence are postprocessed to reconstruct any desired plane. Using the DTS technique, the anatomic relations at the neck of a difficult aneurysm or the three-dimensional relations of vascular feeders to an arteriovenous malformation, to cite a couple of examples, may be shown more clearly. The preliminary studies in dogs (figs. 7 and 8) convincingly indicate that the technique is feasible. The efficacy of DTS in such applications remains to be shown, and we are pursuing this question through clinical studies. The results of these studies will be detailed in a future report.

Another, and perhaps more valuable, potential area of applicability is in conjunction with digital intravenous angiography. Digital angiography has proven useful in the evaluation of major vessels such as the extracranial carotid arteries and the renal arteries. A major limitation for the study of medium-sized and small vessels is the simultaneous opacification of all vessels after an intravenous injection. DTS provides a means whereby individual vessels may be selectively studied by retrospective selection of appropriate tomographic planes. Since multiple different planes can be synthesized, individual vessels can be followed distally even as they change planes. Study of the intracranial vessels with intravenous angiography, for example, has been hampered by the complex pattern of overlapping carotid and vertebral arterial branches. The subtraction angiographic study performed in the dog after aortic arch injection (fig. 8) closely mimics the situation encountered in intravenous angiography. Our preliminary results with tomosynthesis indicate the feasibility of isolating the small intracranial vessels on DTS images for selective study. While much work and refinement remains to be done to make this technique clinically useful, we are pursuing this objective. We are currently modifying our tomographic apparatus and reprogramming the tomosynthesis algorithms in order to enable us to perform various clinical studies, including intravenous digital subtraction angiography.

The DTS technique is not limited to linear tomography. Any tomographic motion including circular or hypocycloidal could be used, but the computer programming to realign the various pixel points for synthesis of a new plane becomes far more complex since motion occurs in two dimensions rather than one, as is the case in linear tomography. Further, the tomosynthesized planes are also not restricted to planes parallel to the 0 plane. As was shown by Baily et al. [5], these planes can be tilted along the longitudinal axis or skewed along the transverse axis, or any combination of tilting and skewing can be performed to a limited degree before distortion renders the image unacceptable. This processing has the potential of selecting a tomographic plane through the body that would be optimal for the organ or blood vessel of interest.

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