THREE-DIMENSIONAL RADIOGRAPHY

D. G. Grant
J. B. Garrison
R. J. Johns

A technique for producing a real three-dimensional X-ray image is described. A set of conventional radiographs of an object is taken, each corresponding to a different viewing angle. The radiographs are photoreduced and placed into an optical system which projects the entire set of images into a display volume where they superimpose. A three-dimensional X-ray image is created in the display volume and is observed by means of a movable viewing screen. The paper presents results obtained with an early experimental model and also describes a prototype system that will be evaluated clinically.

Introduction

OF THE WIDE VARIETY OF RADIOLOGICAL TECHNIQUES EMPLOYED CLINICALLY, none presents the radiologist with a completely satisfactory end product from a diagnostic viewpoint. In conventional radiography, e.g., as with mobile chest X-ray, a point source of radiation projects an entire volume onto a flat film. This collapsed volume image has several undesirable aspects. The most serious of these is that a strongly radio-absorbent volume, such as the heart, which "shadows" a structure of interest behind it, will obscure it or substantially reduce its contrast in the resulting radiogram. In addition, the radiologist has no depth perception and he also must contend with an annoying variation in magnification for structures lying different distances from the X-ray source. Hence, the resultant radiograph, while extremely valuable and useful in aiding diagnosis, still falls far short of providing radiologists with an accurate representation of the structure being X-rayed.

In 1932 Ziedses des Plantes[1] introduced a new concept in radiographic imaging which provided radiologists with a means of selectively imaging flat cross sections of an object. This technique, since named tomography, has many variations but only one guiding principle. Basically, the film and X-ray source (or in some techniques the patient) are scanned through a trajectory which causes the image of a particular subject plane to remain fixed on the film throughout the entire scan. This same scan geometry causes the images of the remaining subject planes to move relative to the film. A complete scan therefore produces a sharp image of a single plane upon which is superimposed blurred images of the remaining subject planes. Researchers have contrived a number of surprisingly effective scan geometries chosen on the basis of maximum image clarity. Linear, and more recently, circular, elliptical, and hypocycloidal trajectories are used. Thus, tomography allows radiologists to actually look "inside" at a particular plane with a minimum of interference from intervening structures. This technique, however, as presently utilized, does have some detracting features. The usual clinical procedure is to tomograph a series of contiguous planes which pass through the volume of interest. This frequently means a set of 10 or 15 complete patient scans to cover the required volume; this may require 30 to 60 minutes. Both the time and X-ray dosage required for this proce-

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[1] Ziedses des Plantes, "Eine Neue Methode zur Differenzierung in der Roentgenographie," *Acta Radiologica* **13**, 1932, 182–192.

dure are larger than desirable. In addition, the radiologist must have *a priori* knowledge concerning the position and orientation of what is sought. If, for instance, the structure is tilted relative to the tomographic plane, his tomograms would be of greatly reduced value. Furthermore, it is conceivable that he could miss the structure entirely if the patient moved or the system was slightly misadjusted.

The three-dimensional X-ray image projector developed by APL and the JHU School of Medicine possesses several advantages over the aforementioned techniques. First, the projector creates a true-size real image in space which is observed by means of a viewing screen. The image on the screen shows the structures lying in a particular plane of the subject. Hence, the image is tomographic in that interfering structures do not appear on the screen and true relative contrast is preserved in the observed plane. The second and most notable advantage is that the viewing screen may be rotated or translated throughout the display volume to show all structures within the subject. The projector therefore forms all tomographic planes simultaneously, including tilted planes, and obviates the need for *a priori* knowledge concerning the position and orientation on internal structures. A third advantage is that the information required to reconstruct the three-dimensional image is obtained with a single X-ray scan of the patient and, hence, suggests the possibility of substantially reducing the required dosage (as compared to conventional tomography).

Image Recording

To simplify the following discussion, the object being X-rayed will be restricted to simple point absorbers. Insofar as the technique is concerned, more complex subjects can be treated exactly the same way as the simple object discussed below.

This system is perhaps best understood as an extension of circular tomography which is shown in Fig. 1. Here, an X-ray point source scans in a circular trajectory of radius R_0 a distance h above the X, Y plane. A point absorber P placed at $\mathbf{r} = X\,\hat{e}_x + Y\,\hat{e}_y + Z\,\hat{e}_z$, where $\hat{e}_x$, $\hat{e}_y$, $\hat{e}_z$ are unit vectors, will project a circle onto the X, Y plane with radius

$$R_z = \frac{Z}{h - Z} R_0. \qquad (1)$$

The center of the circle will be located at

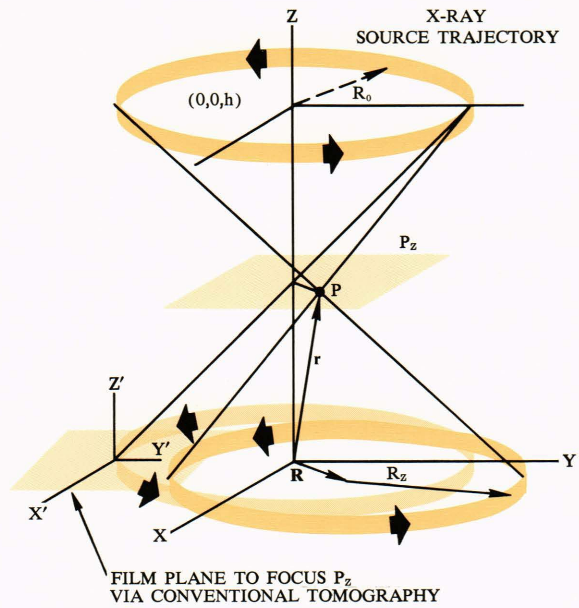


Fig. 1—Circular tomography.

$$\mathbf{R} = \frac{h}{h - Z} (X\,\hat{e}_x + Y\,\hat{e}_y). \qquad (2)$$

It is clear then that points lying in a plane defined by Z = constant will be mapped into a set of circles whose radius is a constant determined uniquely by Z. Furthermore, no two points lying in this plane will map into circles with the same center. Hence the method of projection represents a mapping of points into a unique (center, radius) pair.

The $X'Y'$ coordinate system shown in Fig. 1 represents the X-ray film plane of circular tomography. In this system the film scans a circular trajectory of radius R_z synchronously with the X-ray source. The origin of this system is determined by the projection of $(0, 0, Z)$ onto the X, Y plane. Also, the $X'Y'$ axes are constrained to remain parallel to the X, Y system throughout the scan. This geometry causes the projection of points in the P_z plane to remain fixed throughout the entire scan. The projection of points not in P_z will form small low-contrast circles on the film and thus, will be blurred by the scanning motion. The end result of this process is an image of a single subject plane upon which is superimposed the blurred images of all remaining subject planes.

It has been generally realized that the X-ray system described above projects considerably more information than a single tomographic plane. If one examines Eq. (1), it is clear that the focused

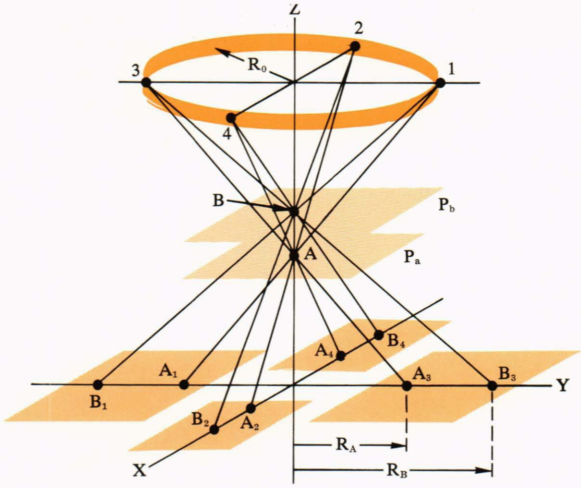


Fig. 2—Fixed position imaging.

plane can be arbitrarily changed by simply changing the scanning radius of the $X'Y'$ plane, (i.e., R_z), while keeping R_0 fixed. This implies that sufficient information is projected during a single scan to reconstruct all subject planes. By projecting onto a continuously moving film, however, all information except that associated with a single plane is destroyed. If, instead, the projected data are recorded on a set of N separate, fixed-position radiographs, they can be utilized to reconstruct the entire subject. This procedure is illustrated in

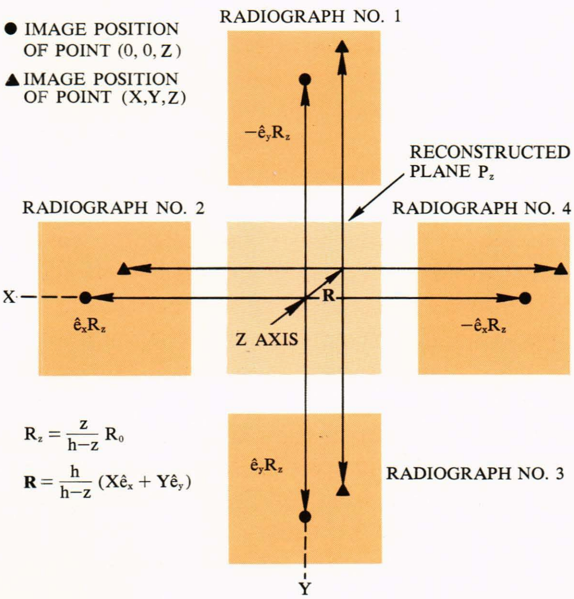


Fig. 3—Data summation for reconstruction of plane P_Z.

Fig. 2 for $N = 4$. Here, points in the $Z = A$ plane and the $Z = B$ plane associated with R_A and R_B respectively are simultaneously recorded. It is obvious that all intermediate planes are also recorded and that no particular plane is favored by the recording process; such is not the case with conventional tomography.

Figure 3 illustrates the summation required to reconstruct an arbitrary plane from the set of radiographs. This figure shows the radiographs in the X, Y plane of Fig. 2 as viewed from the positive Z axis. The reconstruction process for a given

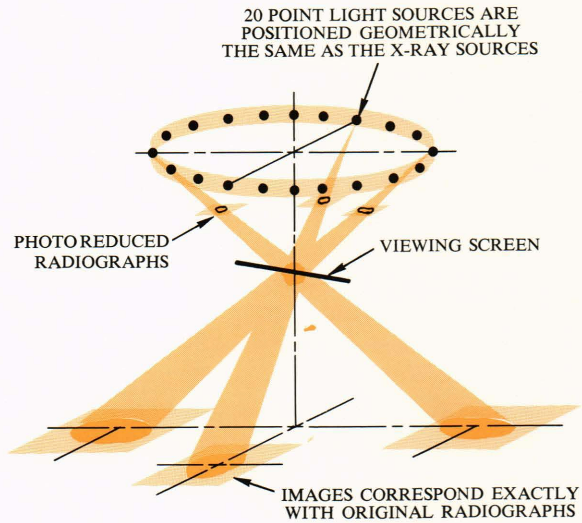


Fig. 4—Three-dimensional reconstruction for circular scan.

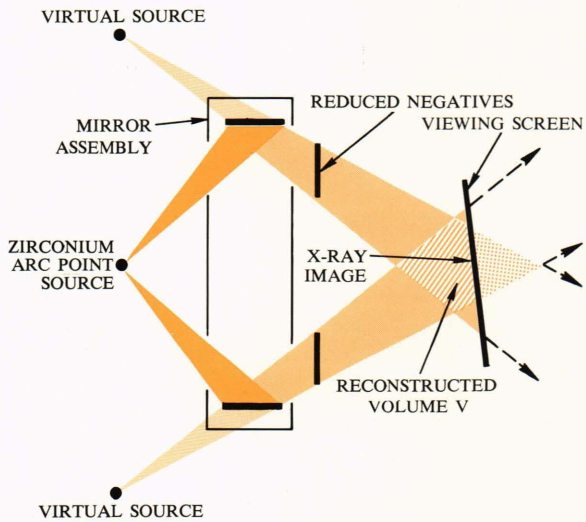


Fig. 5—Three-dimensional projector.

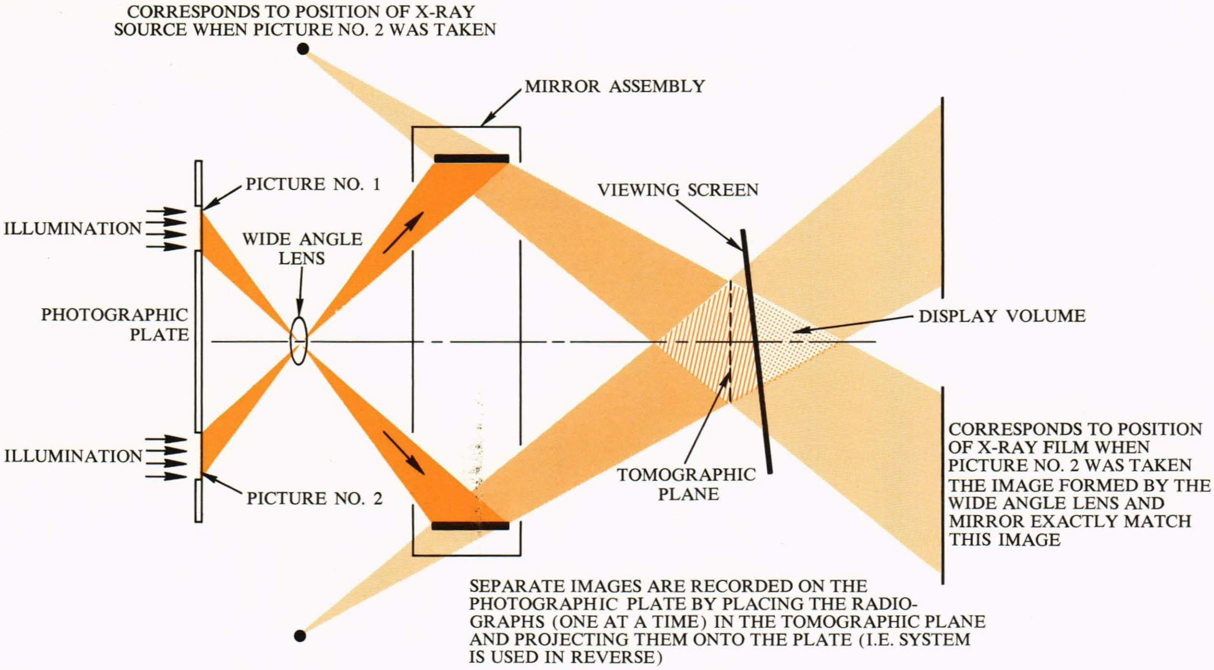


Fig. 6—Three-dimensional imaging apparatus.

point consists of summing the projection of this point from each of the four radiographs. The axial point of plane P_z is therefore found by summing the data points a distance R_z (Eq. (1)) from the origin; (that is, the data located at positions $\pm \hat{e}_x R_z$ and $\pm \hat{e}_y R_z$). Notice that this summation is simply a four-term approximation to the continuous integral of circular tomography. To reconstruct an arbitrary point in the Z plane, i.e., point (X, Y, Z), we simply displace this set of four vectors from the origin by $\mathbf{R}$ (Eq. (2)) and sum the new data points. By moving this quartet of vectors over all space and performing the indicated summation we will reconstruct plane P_z. Any other plane may be obtained by repeating the above process with appropriate values for R_z and $\mathbf{R}$. The extensions of this procedure to large N is straightforward.

Therefore, the recording of N separate radiographs, each from a different view, provides sufficient information to reconstruct a three-dimensional image and where each observed plane is an N term approximation to the continuous integral image obtained by tomography.

Image Reconstruction

The 3-D projection system retrieves data from the N radiographs in a manner that produces a real three-dimensional image. The particulars of this system are a specific example of the previous discussion. In Fig. 4, the X-ray source is moved through 20 fixed positions and radiographs are taken. Let us maintain this geometry and replace the X-ray sources with point light sources. Furthermore, photoreduce each radiograph and place it in front of its corresponding light source so that it projects an exact image (ignoring diffraction) of the original radiograph. A viewing screen placed in the display volume causes the projected images to sum and form an X-ray image of a single plane.

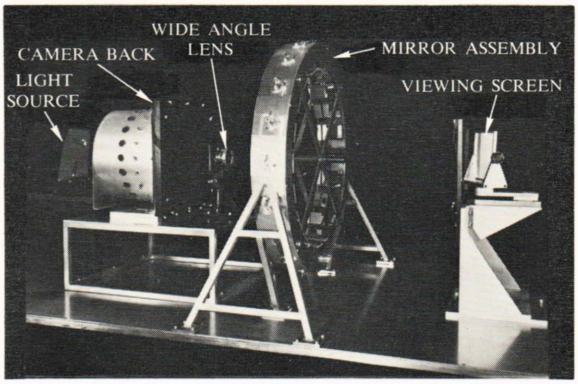
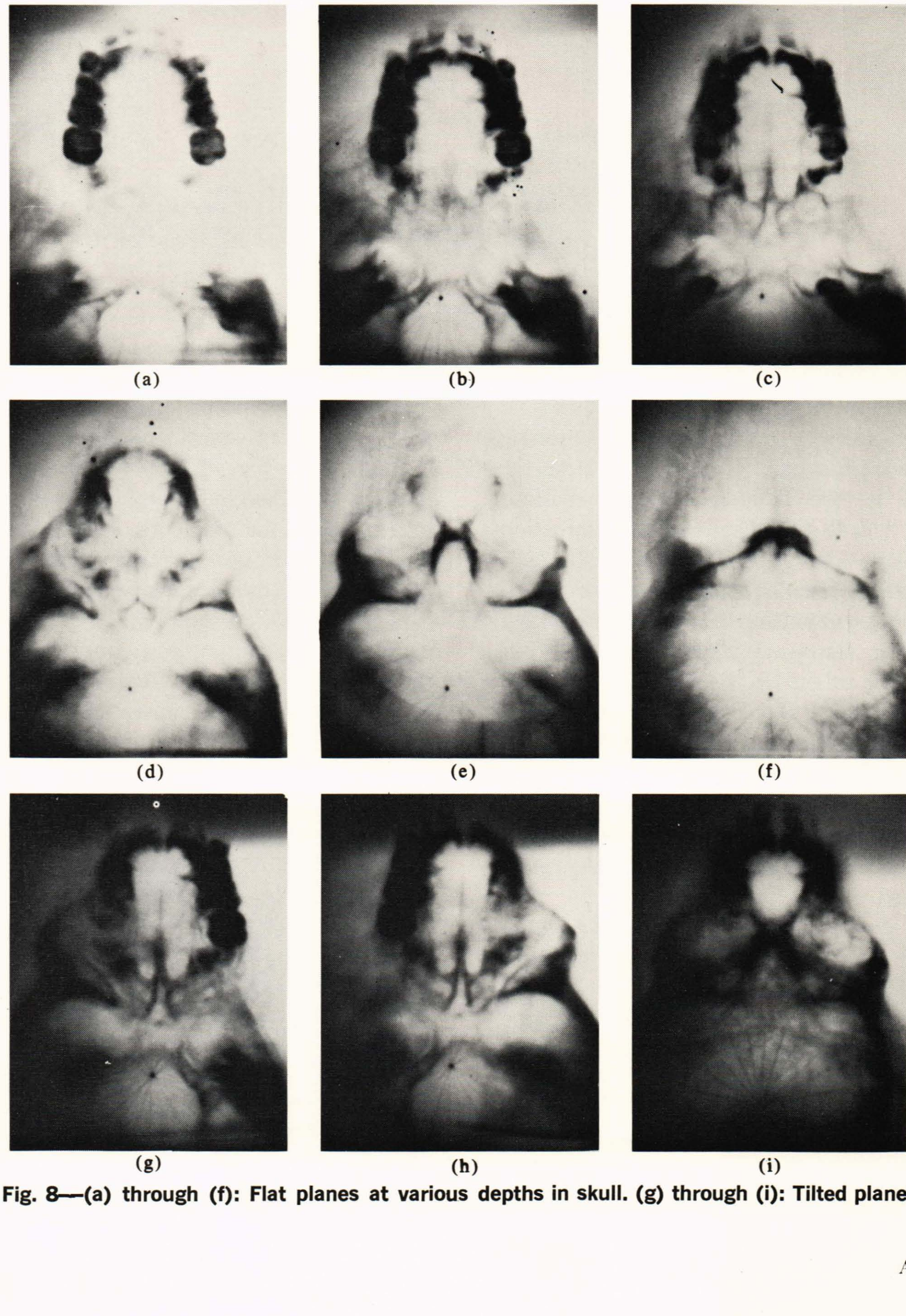


Fig. 7—Three-dimensional imaging system.

By translating and rotating the viewing screen, all structures within the object can be observed. An analysis of the projector in the context of Fig. 3 shows that the data are being summed by the reduced negatives to produce all planes of the object simultaneously and in their exact relative position and size. The computation of tilted planes from Fig. 3 requires a continuous variation of R_z and **R** as the quartet of vectors scan the radiographs. This complex operation is performed automatically by the optical system of Fig. 4 and, hence, all tilted planes as well as planes normal to the Z axis may be observed.

The projection system depicted in Fig. 5 was the first of two optical systems devised to form a 3-D X-ray image. A 100-watt zirconium arc point source was used in conjunction with a mirror assembly to form 20 virtual sources. The photoreduced radiographs were aligned on a detachable support ring which was mounted on the mirror assembly. The images were projected into the display volume forming there a 3-D image. The ma-



(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. 8—(a) through (f): Flat planes at various depths in skull. (g) through (i): Tilted planes.

jor detracting feature of this system was the loss in resolution caused by diffraction between the negative support ring and the viewing screen. A second, higher resolution system was devised and is shown in Fig. 6. Here, the 20 radiographs are first recorded as separate images on a single 11 × 14-inch plate by means of the mirror assembly and wide angle lens (i.e., images are sequentially recorded using the system in reverse). The plate is then processed, placed back into position and diffusely illuminated. The mirror assembly now combines the images in exactly the same geometry as in Fig. 5 except now with much greater resolution. The lens (Schneider Super Angulon 121 mm) is adjusted to provide good depth of focus throughout the entire display volume.

The projection apparatus is shown in Fig. 7. Using the Polytome at Johns Hopkins Hospital, 20 radiographs of a chimpanzee's skull were obtained using a circular scan geometry with a 30° cone half-angle. Images were spaced uniformly about the circular trajectory. The radiographs were processed as discussed above and a 3-D image was formed. Figure 8 shows images obtained on the viewing screen at various depths in the skull.

Summary and Future Plans

The National Institute of General Medical Sciences is presently supporting a joint APL/JHU Medical School effort to develop a clinically useful 3-D projection system. This system will include not only the projector itself but also the associated X-ray and image processing apparatus required to fully exploit the advantages of 3-D radiographic presentations.

A prototype projector has recently been completed that will be evaluated clinically (Fig. 9). This projector generates a display that is larger, brighter, and capable of greater resolution than the experimental system described above and also provides means of remotely scanning the viewing screen through the display volume. A vidicon camera focused on the viewing screen, and which scans with it, provides a continuous high-resolution TV presentation.

To be a clinically useful system a great deal must be done to simplify recording the required 20 X-ray views. A fully automatic means has been devised that produces 20 reduced images on a single film to be used directly on the projector. Development of this apparatus is underway and will be of major concern to the program during the next year.

The three-dimensional X-ray projector should be an extremely valuable diagnostic instrument. Many of the problems that now limit or reduce the effectiveness of radiological investigations will be overcome by the three-dimensional nature of the final image. In addition to these gains, however, there are numerous intriguing potential applications that remain to be exploited and developed. For instance, by timing the X-ray triggering circuitry to the heart cycle, heart volume measurements should be possible. Knowledge of tumor position, size, and growth rate should become more exact with a 3-D image. Radio-opaque techniques can be used to produce 3-D spatial maps of biological structures. The potential exists for employing radiological subtraction techniques in three dimensions.

Fig. 9—Three-dimensional projector, prototype system.

Major effort during the next year will be directed at producing a 3-D image of a chest volume. Once the 3-D system is established clinically and accepted by the medical community its domain of application will increase considerably.

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