# The Humongotron—A Scintillation-Camera Transaxial Tomograph

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*An emission transaxial tomographic system using a scintillation camera as the detector is described. The unit allows accurate positioning of a scintillation camera's detector at any angle around a patient in order to obtain the multiple projection images needed for transaxial tomography, and it is capable of imaging any area of the body. The camera can also be used for all types of conventional imaging procedures. Image processing is performed by a small on-line computer. A convolution algorithm and a mathematical technique for approximate absorption correction are used to obtain high-resolution and high-contrast images with good quantitative accuracy. The operation of the system is described and representative phantom and patient studies are presented to illustrate the capabilities of the system.*

Although the medical applications of what is now known as computed tomography (CT) were actually first shown in 1963 in the field of nuclear medicine by Kuhl and Edwards (*1*), emission CT technology has lagged far behind transmission CT in clinical practice and, as of this writing, there is not yet a commercial system for emission CT imaging. Among the many reasons for this lag has been the lack of a suitable imaging system to gather the multiple projection images needed to produce CT reconstructions. A number of systems have been proposed to overcome this lack. Several of these approaches and their associated problems have recently been reviewed (*2*).

We have felt that one of the more promising approaches would be to use an Anger camera as the heart of an emission transaxial tomograph. We have been investigating this approach for several years. This paper introduces a clinically useful scintillation-camera tomograph, describes the function and capabilities of the machine, and reports its usefulness in preliminary clinical trials.

## DESIGN CONCEPT

Phelps et al. (*3*) recently listed the following as the essential requirements for an emission transaxial tomographic imaging system: (A) the ability to produce images with good contrast and spatial resolution; (B) the ability to correct accurately for attenuation; (C) uniform spatial resolution and sensitivity across the image plane; and (D) high detection efficiency. In addition to these features, we feel that such a system should also: (E) allow imaging of any part of the body; (F) be simple and fast to operate; (G) have the ability to do conventional imaging as well as tomography; and (H) be economi-

cal both in terms of initial cost and in day-to-day operation.

With the exception of points B and C, the scintillation camera represents a very good match to the above design requirements. Two of the primary problems in developing a scintillation-camera emission tomograph relate to the severely depth-dependent resolution and sensitivity of the scintillation camera and to the lack of an analytic method to correct exactly for attenuation losses. Kay et al. (4,5) have shown, however, that partial compensation for non-uniformity of resolution and sensitivity can be achieved by using averaged opposed views. For parallel-hole collimators with gradual fall-off in resolution (i.e., long holes) the correction achieved can be very good. Such collimators have other advantages, as will be shown later. In addition, Kay (4,5) and Budinger (6) have shown that approximate but satisfactory attenuation corrections can be made during the reconstruction process by assuming a uniform distribution of absorber within the object as a first-order approximation and applying this to the projection data in various ways.

The ability to acquire data in digital form and perform the necessary calculations is, of course, essential for CT imaging. There are several small computer systems available that are designed to interface easily with the scintillation camera and are capable of performing the computations necessary for CT.

We thus chose to develop a tomographic system that would utilize as much of this existing technology as possible. A primary design consideration was to add tomographic capability to the scintillation camera without compromising its usefulness in other applications. To accomplish this we developed the following specifications for a camera-based transaxial tomograph:

1. The device should use the detector and electronics of a standard scintillation camera.
2. The detector must be able to rotate in a full 360° circle around the patient and obtain images in any rotational position.
3. The detector must be able to move in and out relative to the axis of rotation in any rotational position.
4. The device should allow tomographic imaging of any portion of the body.
5. The device should allow the performance of all conventional nuclear medicine imaging procedures.

Figure 1A depicts a system we have designed and constructed which meets these specifications.

### MECHANICAL DESCRIPTION

Figure 1B shows the mechanical structure of the device. The detector is mounted on a cross beam that is free to move up and down on two heavy support columns through dual pillow-block and ball-bushing supports at each end. Up-and-down motion is accomplished by a drive screw behind the right-hand support column. The drive mechanism is similar to that used in a standard camera mount. A set of counterweights is connected to the detector's support beam through paired roller chains and
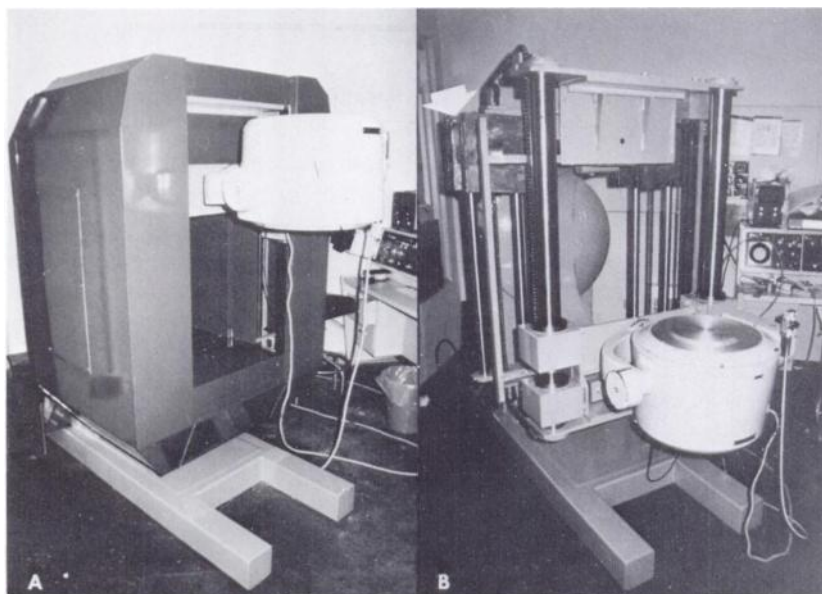


FIG. 1. (A) Humongotron in operational form. (B) Unit with outer sheet-metal covers removed to show major mechanical features. Arrow points to one of paired counterweights.

sprockets. The counterweights can be seen behind the support columns in Fig. 1B (white arrow). The weights counterbalance the weight of the detector-yoke–support-beam assembly and move in the direction opposite to this assembly relative to the axis of rotation. These weights have been adjusted so that the unit remains in neutral balance around the axis of rotation for any position of the detector. Two speeds are provided for in-and-out motion of the detector counterweight assembly: fast for rapid positioning, and slow for fine adjustments near a patient.

The entire detector and counterweight assembly is carried on a C-arm cantilevered by a massive circular bearing assembly mounted in the upright housing at the rear of the unit. Rotational motion of the C-arm through a full 360° circle in either direction is accomplished through a worm-gear drive attached to the C-arm bearing. Speed of rotation in either direction is continuously variable from zero to one revolution per minute. Rotational position is read out electronically from a resolver attached to the C-arm bearing. This provides angular position both to the computer and through a visual display for accurate hand positioning.

The detector itself is a standard Pho/Gamma HP camera,* including the yoke assembly, which has simply been unbolted from the standard mounting stand and reattached to our unit. The pivoting motion normally provided at the yoke's mounting point has been eliminated since this motion is provided by C-arm rotation. The camera's electronics are unaltered. The detector is connected to the standard console through an extra-long cable that permits full rotation and positioning flexibility.

Patients are positioned along the axis of rotation by means of a cantilevered table. This is adjustable for height and fore-and-aft position, allowing the detector to be brought into apposition with any part of the body at any angle of rotation. An illustration of this table in use is shown in Fig. 2. The table top is constructed of a rigid honeycomb material that provides excellent support while minimizing gamma-photon attenuation. Actual table-top attenuation losses for $^{99m}$Tc average approximately 5%, increasing to 15% for a small range of angles near the plane of the table top.

## OPERATION AND PERFORMANCE

Operation of the Humongotron is almost completely conventional. All standard scintillation-camera accessories can be used with the unit, including collimators and collimator carts. For routine imaging, standard patient-imaging tables can be used as well as the special cantilevered table. Figure 2



**FIG. 2.** Unit in use, showing rotational capability and patient positioning on cantilevered table.

shows the machine setup for an oblique view of the spleen.

Data acquisition is also conventional, routine studies being done as they would with any camera. For digital data acquisition, as is required for tomography, the camera is interfaced to a "Trinary System."† For tomography, sequential rotation views at predetermined angular increments are acquired in a 64 × 64 matrix and stored on disk. During reconstruction, profiles corresponding to the desired tomographic level are read from the stored images, and these serve as the projection data for the reconstruction program.

The angular intervals required in order to reconstruct an image with no loss in detail can be predicted from theoretical considerations (6,7). For a circular image, 25 cm in diameter (i.e., the camera's field of view), digitized into a 64 × 64 matrix, a perfect imaging system would require approximately 200 views at equal angular increments around a 360° circle. In practice, the scintillation camera is not a perfect imaging system and the intrinsic resolution of the camera can be reproduced with approximately 100 equally spaced views. We have used 120 views at 3° increments in studies in which we wish to be sure that reconstruction accuracy is not limited by inadequate sampling. Since the camera's resolution in actual application is less than its intrinsic resolution, fewer than 100 views will, in general, be required. We have used 60 views at 6° intervals for most phantom studies with excellent results. For patient studies where time considerations are important, we have used 30 views at 12° intervals, realizing that this may be sacrificing some resolution. The actual resolution loss due to use of a limited number of projections is less than would be predicted by theory; this effect has been shown by Budinger (6) and confirmed in our own laboratory.

Our computer has been modified by the inclusion
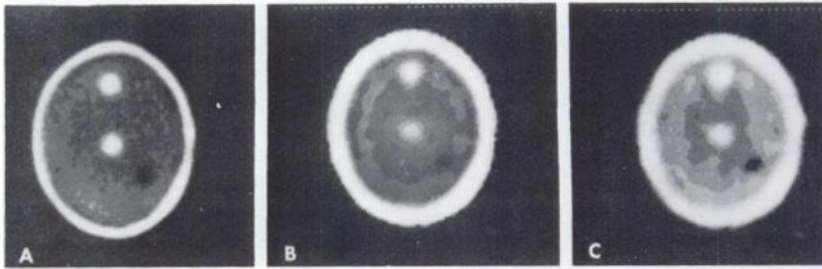
**FIG. 3.** Reconstruction of head phantom; 120 projections at equal 3° intervals were used. (A) Top view of phantom represents theoretical "ideal" reconstruction. (B) Reconstruction without absorption correction. (C) Reconstruction with absorption correction.

of a hardwired floating-point processor‡ and a hardwired multiply–divide board.‖ In this configuration, a tomographic reconstruction from 30 projections requires about 30 sec. Larger numbers of projections add approximately 0.8 sec per projection to this reconstruction time.

The reconstruction algorithm that we have been using is of the convolution or filtered-backprojection type that has been extensively discussed elsewhere (6–9). We have modified the basic algorithm to incorporate attenuation correction by Kay's "mean exponential technique" (4,5).

The Humongotron is now installed and is in regular use for day-to-day studies in our clinical laboratory. All conventional imaging procedures are accomplished without difficulty. Our technologists have been able to operate the machine without problems.

We have found that the use of rotational motion together with the cantilevered table makes a number of conventional imaging procedures easier. For example, all views for conventional liver–spleen imaging can be obtained without moving the patient. This is particularly advantageous for patients who are disabled or uncooperative.

Preliminary experience with tomographic imaging has also been extremely encouraging. Some representative examples of studies performed with the unit will serve to illustrate the type and quality of image that can be achieved. Data for all studies presented here were gathered using a high-resolution low-energy collimator. This camera–collimator combination gives $3/16$-in. resolution at the collimator face, which would represent the limiting resolution of the system.

Figure 3 is a reconstruction of a head phantom, a cylinder measuring 17 by 20 cm. The outer hot rim representing superficial scalp activity is 0.6 cm thick, and the two inner hot "lesions" and the cold "lesion" are each 1.5 cm in diameter. Between the "scalp" and the inner "cortical" activity is a 0.5-cm-thick layer of sand representing the skull. The "scalp" and the hot "lesions" contain ten times as much activity per cubic centimeter as the "cortex." There is no activity in the skull or the cold "lesion."

The total activity in this phantom was 1.5 mCi. This phantom is constructed so that the "lesions" are cylindrical and of the same depth as the phantom, with their axes parallel to its central axis. Consequently, every transverse section of the phantom is identical to every other, and a top view of the phantom is representative of what each transverse section should look like. Figure 3A is such a top view.

Figures 3B and 3C are reconstructions from identical data. Figure 3B was reconstructed without attenuation correction and Fig. 3C with it. Each reconstruction was made from 120 projections at 3° increments. Each projection contained approximately 6,000 counts.

Figure 4 shows more clearly the effectiveness and limitations of the attenuation-correction routine. The object is a cylinder of pertechnetate solution 15 cm in diameter. The profile shows the correction that is possible. This figure also exhibits an artifact due to camera nonuniformity. We have found that careful camera tuning to ensure that field nonuniformities
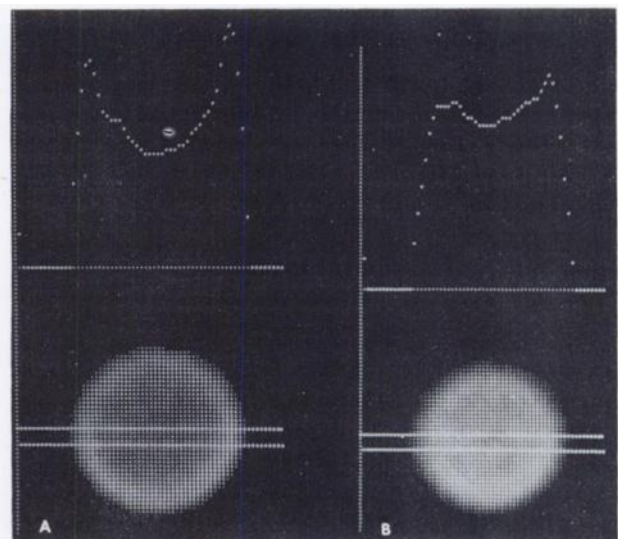


**FIG. 4.** Reconstruction of uniform absorption phantom, using 60 projections at 6° intervals. (A) Without absorption correction; (B) with absorption correction. Side-to-side asymmetry is artifact due to camera-field nonuniformity.

are both minimal and symmetric around the axis of rotation is essential to high-quality tomography.

These figures do not illustrate the resolution capability of the tomographic system well. Under optimal circumstances we can achieve a resolution of 8–9 mm in our reconstructions. Under the conditions present during patient studies, the resolution is between 1.5 and 1.8 cm.

Figure 5 shows several contiguous sections of a pertechnetate study in a normal individual. This can be compared with Figs. 6A and 6B, which are studies of a patient with a large metastic tumor that has eroded through the calvarium and extensively involves scalp, bone, and underlying brain. Figure 6A shows representative sections of a pertechnetate brain study on this patient. The extent of tumor, patricularly in the brain, is readily apparent. Figure 6B shows corresponding sections from a $^{99m}$Tc-pyrophosphate study. The abnormal reactive bone uptake and the large defect in the calvarium can be seen, but there is no accumulation of tracer within the soft tissue of the tumor. These studies were obtained with 15 mCi each of the respective radiopharmaceuticals.

The latter study clearly shows one of the potential advantages of tomography, namely, the ability to separate extensive skull and scalp activity from underlying brain. In postoperative patients suspected of having recurrent tumor, this question is frequently impossible to resolve with conventional brain imaging.

We have also found by tomography lesions at the base of the brain that were not seen on conventional radionuclide studies, and this appears to be another area where tomography could be extremely useful. Clinical trials are currently under way to evaluate more fully the utility of the technique.

### DISCUSSION

The Anger camera appears to be a favorable instrument for CT data-gathering. It fulfills most of the criteria felt to be desirable in an emission CT system, and technical or mathematical means can be used to circumvent its weaknesses. In addition, the camera possesses several distinct advantages over other systems that have been proposed.

The Anger camera is a highly developed and widely available imaging system that is nearly ideal for technetium imaging. As most present-day nuclear medicine procedures are based on technetium radiopharmaceuticals, camera CT imaging can be accomplished with currently available radiopharmaceuticals and would not require the development of radically new and different radiopharmaceutical technology, as would positron emitters, for example.
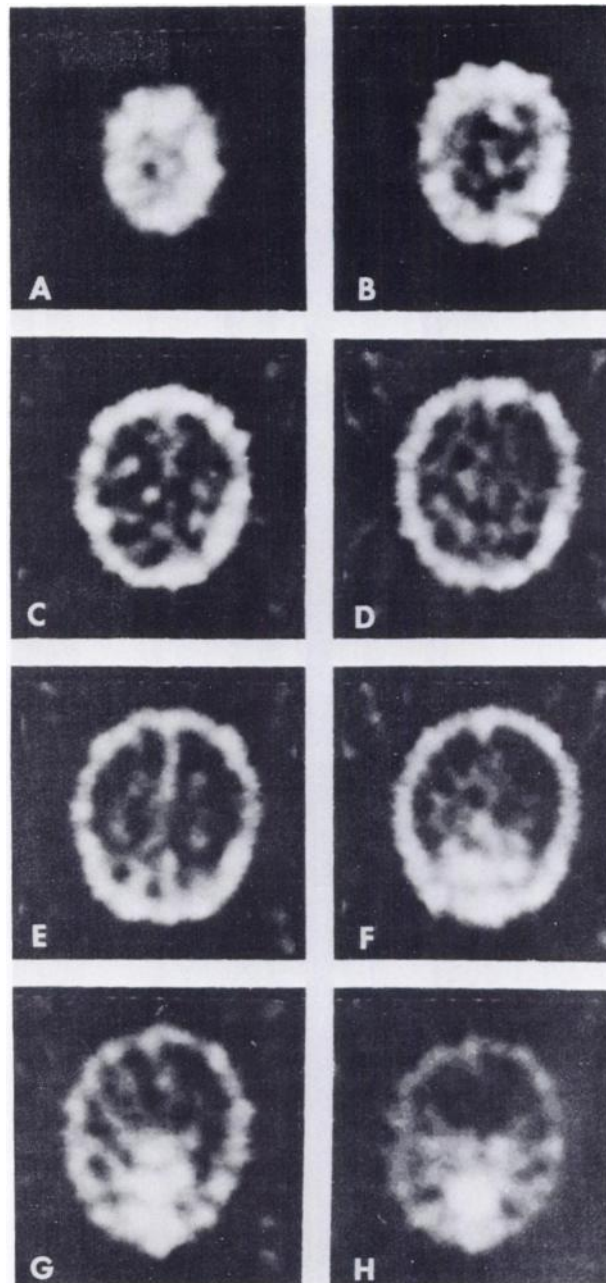


FIG. 5. Pertechnetate brain study of normal patient, using contiguous 1.5-cm sections and 30 projections at 12° intervals. Data-acquisition time was about 0.5 hr. In this and other patient studies, nose is down and sections are viewed from above. Anterior activity seen in sections F–H corresponds to uptake in nasopharynx and cavernous sinus. Stippled "snow-like" appearance of central portion of sections is felt to be reconstruction artifact due to data noise rather than real structure.

The camera, as noted, is also capable of performing all conventional imaging procedures, including dynamic studies. By preserving this capability in a camera tomograph, the system actually gains flexibility and utility.

The camera is also a two-dimensional imaging de-
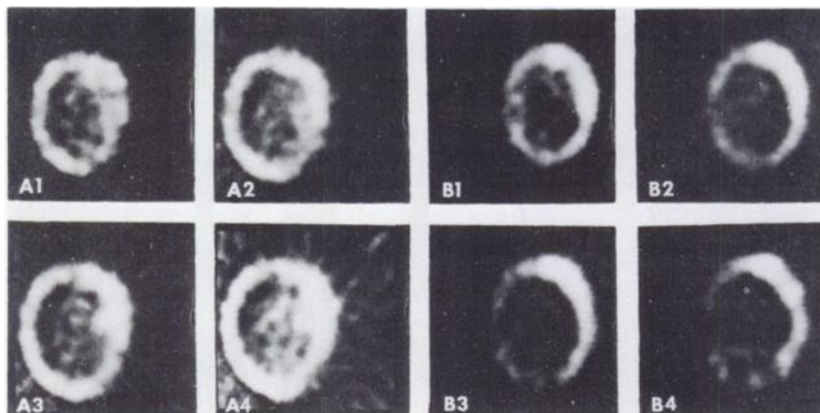
**FIG. 6.** (A) Pertechnetate brain study of patient with metastatic carcinoma. Contiguous sections are 1.5 cm thick from 30 projections at 12° intervals. Irregularity in skull contour seen anteriorly in section A4 is artifact due to patient movement. (B) Corresponding sections of same patient studied with $^{99m}$Tc-pyrophosphate.

vice. This means that during a single data-gathering pass, sufficient information is obtained to reconstruct multiple tomographic sections. For example, in the studies shown, the actual imaging time was approximately 30 min. Since 8–10 sections, 1.5 cm thick, are required to examine the head fully, this is actually equivalent to an imaging time of less than 4 min per section. This point has been overlooked by some investigators (3) in assessing the relative efficiency of various approaches to tomography.

Although at present both routine and tomographic images are considered necessary, a complete tomographic study of the head may be all that is needed. In effect, a complete set of tomographic images comprises a full three-dimensional reconstruction of the organ under examination and additional projection images are redundant. Indeed, routine two-dimensional projection images can be synthesized from a full three-dimensional reconstruction if this is desired.

Further development of the Humongotron is planned. As noted above, parallel-hole collimators with relatively long holes are advantageous in that they both minimize detector resolution fall-off with depth and also permit better compensation for this fall-off using averaged opposed views. In addition, the forward extension of a thicker collimator permits the collimator face to be brought into closer apposition to the patient's head without interference from his shoulders and the collimator support ring. This in turn contributes to better resolution. We are currently developing several collimator designs to take advantage of these points.

Although the Humongotron has been designed to permit imaging of any portion of the body, we have so far limited its tomographic investigations to the head. The head represents an ideal region for such preliminary studies as it is easily immobilized and contains a great deal of internal structure. Other organs, such as the liver, present a number of special problems, such as respiratory motion and large size, which we felt should be approached as separate problems.

Such organs as the liver, whose size exceeds the field of view of the camera, present unusual difficulties for tomographic imaging. Although Oppenheim (10) has shown that objects larger than individual projections can be reconstructed satisfactorily, it would require a major modification of our existing reconstruction program to do this. An alternative approach would be to increase the field of view of the camera to encompass a large organ. To accomplish this, we plan to investigate the use of a diverging collimator and one of the reconstruction algorithms based on fan-beam geometry. Preliminary work also suggests that the fan-beam algorithms would be applicable for use with a converging collimator as well. Proper design of a converging collimator might allow almost perfect compensation for resolution loss with depth, together with decreased sensitivity to attenuation losses.

Another area we are investigating is the use of continuous rather than intermittent sampling. Instead of stopping the camera, acquiring an image, then moving to the next angular position, the camera can be rotated continuously and images acquired over sequential small angular increments. Since no time is then wasted in repositioning the camera between views, we anticipate an approximately 30% reduction in data-acquisition time. Also the close angular spacing eliminates any problem of inadequate angular sampling.

The Humongotron is also designed to allow future incorporation of a whole-body scanning feature. By revising the yoke mounting to allow the detector to swivel 90° and by rotating the C-arm to a horizontal position, the detector could be driven transversely in the same fashion as current scanning cam-

eras are. With this added capability, the unit would represent a truly universal imaging device capable of virtually all present nuclear medicine procedures.

## FOOTNOTES

\* Searle Radiographics, Des Plaines, Ill.
† Medical Data Systems, Ann Arbor, Mich.
‡ Model FP-09, Floating Point Systems, Portland, Ore.
|| Data General, Southboro, Mass.

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