INCREASED RESOLVING POWER FROM SCINTILLATION CAMERAS USING ELECTRONIC SIGNAL PROCESSING AND A MOVABLE FILTER PLATE

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A method has been developed which significantly improves the spatial resolving power of the overall system when used in conjunction with an Anger scintillation camera. By systematically sampling selected and isolated regions of the scintillator (with a movable filter-hole plate) and executing an electronic correlation and manipulation of the resultant signals (on an event-by-event basis), the spatial resolving power has been improved approximately 35%. However, as a consequence of using the filter-hole plate, the sensitivity of the system is approximately 1/3 that of the normal collimator-scintillator camera system. Using the filter scan system (with filter-hole dimensions less than 1/4) it is possible to resolve an 1/8-in. lead bar phantom when placed near the surface of the system. Also, a 3/16-in. bar phantom can be resolved when placed at a distance of 4 in. from the system surface.

The limitations of the system have been described (namely, sensitivity loss and "ghosting") and clinical evaluation is required to determine an acceptable compromise while a theoretical approach is necessary to optimize the several parameters of the system. The filter scan system has been adapted to a tomographic scintillation camera and although artifacts may limit usefulness, the 3/16-in. bar phantom has been resolved when placed in the plane of focus at a distance of approximately 2 in. from the surface of the system.

For the past few years scintillation cameras have been increasingly used in a clinical environment to visualize radionuclide distributions. An early description of such a device has been presented by Anger (*1,2*). During this period there has been an active interest in the importance of spatial resolving power [see, for example, Vetter, et al (*3*), Baker, et al (*4*), and Anger (*5*)]. In the following sections of this paper an operational system is discussed whereby the spatial resolution of a scintillation camera-collimator unit is improved. Furthermore, experimental results on phantoms using this system are directly compared with results obtained from a normal camera.

MATERIALS AND METHODS

Anger scintillation camera and intrinsic resolution factors. A typical scintillation camera uses a single, large-diameter, thin, thallium-activated sodium iodide crystal to view the gamma-ray emitting source. An array of photomultiplier tubes is arranged to convert the scintillations occurring in the crystal into electrical impulses. The signal from each photomultiplier tube is amplified and given a weight according to its geometric position in the array. These appropriate portions of the signals from all of the photomultiplier tubes are then combined to produce X and Y deflection voltages which are coupled to the deflection circuits of an image-readout oscilloscope. If the total energy (proportional only to the brightness of the scintillation) deposited by a gamma ray in the NaI(Tl) crystal lies within a preselected range (appropriate to the radionuclide being observed), then the cathode-ray tube is allowed to display a flash approximately corresponding in position to where the scintillation occurred in the crystal. Thus, using suitable collimation an image is produced from the individual scintillations by photointegration.

The *system* (overall) resolving power of the Anger scintillation camera-collimator unit is a function of

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the geometric parameters of the collimator used to project the gamma rays from the source onto the scintillator and the conversion of this projected gamma-ray image into a visual representation by the scintillator camera. The latter component comprises the inherent resolving power of the scintillation camera and is effected by the statistical nature of the division of photons which have resulted from a single scintillation among the various photomultipliers, and to a lesser degree the multiple scattering of gamma rays within the scintillator (*5,6*). The filter scan system described in the present paper basically reduces this inherent resolution to zero (i.e., a means is presented whereby the overall scintillator camera system resolution may be markedly improved by permitting a moderate reduction in sensitivity of the device). In essence a filter plate (Fig. 1) permits selected and isolated regions of the scintillator to be sampled simultaneously. An electronic correlation and manipulation of the signals results in flashes on the readout oscilloscope corresponding to the most probable points of origin of the signals (i.e., at positions corresponding to the central points of the filter holes of the plate). Since these filter-hole dimensions are in general smaller than the intrinsic camera resolution, an improvement in overall resolution results. The full area of the crystal is covered by moving the filter plate in a small raster. By this means an analysis of sampled portions of the scintillator is performed on an event-by-event basis.

The use of a movable gamma-ray multiaperture plate and a movable optical aperture plate (placed in front of the CRT) to improve the resolution of scintillation cameras was first suggested by Larsson (*7*). The optical aperture plate moves in synchronism with the gamma-ray aperture plate, and only flashes on the CRT that occur within the apertures of the optical mask are allowed to be photorecorded. The present electronic network eleminates the difficult problem inherent in Larsson's model of mechanically moving the optical mask in a synchronistic motion with respect to the gamma-ray aperture plate. Furthermore, and most importantly, a gain in sensitivity is obtained with the present system due to the inclusion of pulses which lie outside the apertures of the optical mask (in Larsson's model).

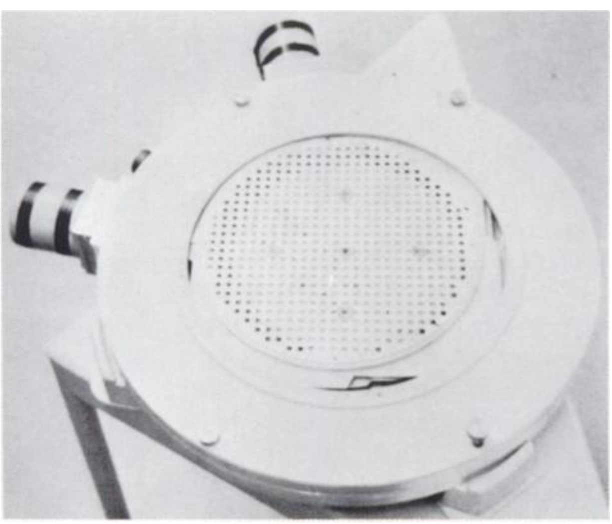

FIG. 1. View of filter plate (mounted in filter plate/collimator assembly and detached from scintillation camera) similar to one described in present paper. Square holes are arranged in square array having center-to-center spacing of about 12 mm. Composition and thickness of filter plate are presented in text. Stepping motors and five selected tuning hole positions are visible.

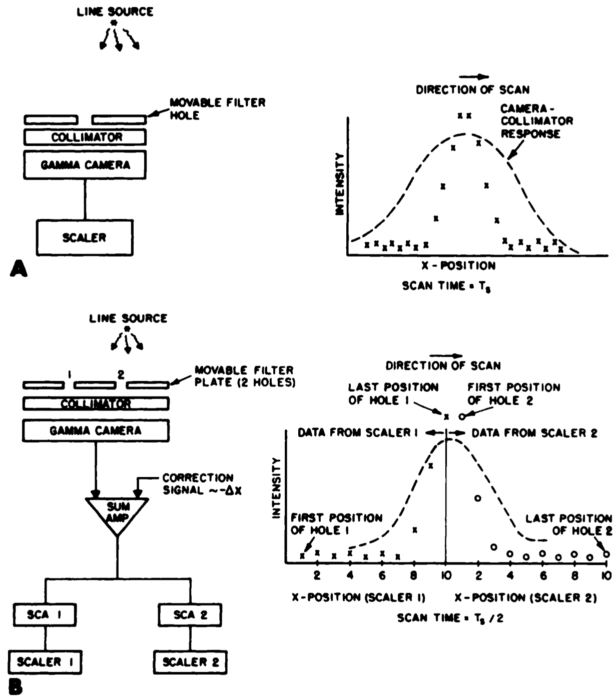

FIG. 2. A illustrates the use of single filter hole in radiation opaque plate to improve camera-collimator system response, in hypothetical system. B illustrates use of two filter holes in similar manner to decrease total data collection time. Dashed line schematically represents normal scintillation camera response.

Principle of operation. The present multiaperture method can best be understood by considering the two hypothetical experiments schematically shown in Fig. 2. At the top of Fig. 2 is shown an experiment consisting of the use of a *single* movable filter hole placed above a gamma camera and collimator. Assume that the intrinsic resolution R_1 of the gamma camera is larger than the combined resolution of the collimator-filter hole system. A line source is placed above the system. The gamma camera networks amplify, energy discriminate, and shape the pulses from the detector. Thus it is possible to record the counts obtained from the scaler for a preselected time at each of several X positions of the filter hole. If one were to plot the counting rate as compared with position (X direction) of the filter hole, a plot such as that shown in the upper right of the figure might result. There is an improvement in the spatial resolution as compared with the normal response of the camera shown schematically by the dashed curve. The total time for the scan may be designated by T_s.

Consider now a second hypothetical experiment designed to decrease the scan time through the use of two filter holes instead of a single aperture. An analysis of the circuit shown at A indicates that it is unsuitable if used with more than one filter hole; however, one possible circuit that would function with two filter holes is shown at B in Fig. 2. The gamma camera and collimator are the same, but now a *summing amplifier, two single-channel analyzers* (SCA), and *two scalers* are used. It is assumed that the filter holes have been sufficiently separated so that there is little overlap between their two spatially dependent (X-positioning) pulse distributions (resulting from the inherent resolution). At the initial position of the plate it is possible to adjust SCA 1 so that its "window" appropriately brackets the X-position pulse distribution resulting from filter hole 1. Similarly, SCA 2 is adjusted so that its window brackets the pulse distribution resulting from filter hole 2. For the proper operation of this circuit one further procedure is necessary. As the filter plate is moved (in the X direction), thus producing a shift in the most probable values of the spatially dependent pulse distributions from the two filter holes, a correction signal proportional to the displacement ΔX (in the negative sense) is applied to one input of the sum amplifier. This procedure causes the pulse distributions at the output of the sum amplifier to be properly included within the *preselected fixed* windows of SCA 1 and SCA 2 independently of any X motion.

It is possible to plot the counting rates of SCA 1 and SCA 2 as compared with the positions of the respective filter holes. A plot such as that shown in the lower right of the figure might result. Note that the counting rate for the first position of hole 2 is "high" since the line source is directly above hole 2 for this position. Similarly the counting rate for the first position of hole 1 is "low" since the line source is *not* directly above hole 1 for this position. Again the spatial resolution is improved for the system as compared with that of the conventional gamma camera and collimator system (dashed line). However, comparing experiment B with A it can be seen that for B only half as many data points need to be measured. Thus, the scan time is now equal to $T_s/2$.

One extension of the above hypothetical experiments is to use as many filter holes as feasible, i.e., spaced as close together as possible in an achievable array such that their respective spatially dependent pulse distributions still only overlap negligibly. By this means the scan time would be considerably decreased. The next section describes one workable method of accomplishing this extension.

Movable multiaperture plate and electronic signal analysis system. The main components of a multiple filter-hole scan system are shown in Fig. 3. In order to simplify the description, only four filter holes and four positions of the plate have been shown in the figure. For clarity the various positions of the filter plate have been shown displaced above the plate at position 0. It is again assumed that the center-to-center hole spacing distance of the filter holes is sufficiently large so that the spatially dependent pulse distributions resulting from adjacent holes overlap only negligibly. This implies that the diameter of the filter holes is less than the combined spatial resolution of the camera and collimator system.

The overall line-spread response function of the filter plate, collimator, and scintillation camera is a complicated function of parameters such as hole size, shape, spacing, collimator response, and camera response. In this paper the improvement in system resolution has been evaluated mainly through a comparison of images of standard phantoms.

System description. Figure 3 can be used to explain in principle the operation of a movable multiaperture plate and electronic signal analysis system. The details pertaining to the actual implementation of such a system is beyond the scope of the paper; however, additional information relating to the actual implementation may be obtained from the author.

Various spatially dependent pulse distributions (assuming, for example, a uniform gamma-ray source is being viewed by the system) are shown in Fig. 3 at selected locations in the system for each of the four plate positions. The pulse distributions have been shown displaced above the distribution for the plate at position 0. The first set of distributions (located in the figure just below the system labeled collimator and gamma camera) correspond to the normal gamma-camera spatially dependent voltage signals (after amplification, energy discrimination, and shaping of pulses). Note that the most probable values of the distributions for each position of the filter plate are shifted by a uniform amount (directly proportional to the spatial displacement of the plate) with respect to those corresponding to the next preceding filter plate position. It is assumed that the filter plate is displaced by a constant amount between any two adjacent positions.

The first correction network has been designed such that a voltage (that is directly proportional to

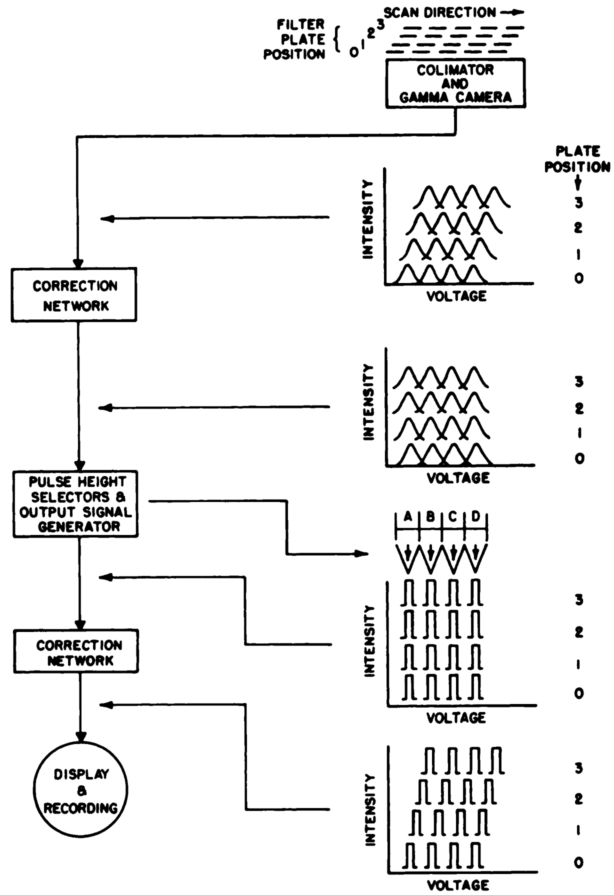

FIG. 3. One method for using multiaperture (filter) plate with collimator and scintillation camera to improve spatial resolution of system is shown. Four plate positions are shown. Plate positions are shown displaced above first position (position 0) for clarity only. Pulse distributions (intensity as compared with pulse amplitudes) for four plate positions of filter plate are shown in right portion of figure. Functioning of system is discussed in text.

the displacement of the filter plate) is subtracted from each spatially dependent voltage pulse resulting from the gamma camera. For example, for pulses corresponding to plate position 0 the displacement is zero, thus, a zero voltage level is subtracted, and the pulse distribution resulting at the output of the first correction network is equal to the original pulse distribution. For the remaining plate positions the voltages subtracted have such amplitudes that the most probable values (at the output of the first correction network) of the pulse distributions are precisely aligned with those resulting with the plate at position 0.

In Fig. 3, the circuit labeled pulse-height selectors and output signal generator is designed such that the output distributions occurring at the output of the first correction network are properly "funneled" into discrete voltage values (which correspond to the most probable values of the individual pulse distributions). There is a single voltage value for each filter hole. This funneling process can be considered as an on-line integration of the raw data within appropriate regions (labeled A, B, C, and D in Fig. 3), and then placing the integrated value at appropriate discrete positions (beneath the arrows in Fig. 3). A convenient means of accomplishing this funneling effect is to use an analog-to-digital converter (ADC) adjusted so that there exists one channel per filter-hole pulse distribution. The digital data may then be used as the input to a digital-to-analog converter (DAC) to generate the discrete voltage pulses shown in Fig. 3.

The final correction network is designed so that a voltage equivalent to the one *subtracted* by the first correction circuit is *added* to each pulse. This process will properly displace the discrete voltage distributions resulting from each position of the filter plate relative to values obtained with the plate at position 0. These discrete voltage distributions may then be recorded in the usual manner (e.g., by photointegration). With such a system the gamma-ray source can be sampled and imaged by properly positioning the filter plate and providing the appropriate correction signals.

For the above discussion it has been assumed that data are collected only while the plate is stationary although this is not a strict requirement. Although only a one-dimensional system was described, it is apparent that a two-dimensional system essentially requires only a duplication of the circuitry.

A two-dimensional system was used to obtain the results discussed in the next section. An ADC/DAC system was used to perform the funneling process while the necessary correction voltages were generated with an auxiliary DAC according to the position of the filter plate. Stepping motors were used to properly position the filter plate at predetermined positions.

RESULTS

For purposes of evaluation the system was attached to a Nuclear-Chicago Pho/Gamma HP scintillation camera. The filter plate system is self-contained and does not interfere with the normal operation of the scintillation camera console. The filter plate-collimator attachment may be easily removed from the detector head, thereby permitting standard collimators to be attached to the head. The filter plate (see Fig. 1) selected was made from lead with 0.6-mm aluminum sheets epoxied to both sides prior to fabrication of the holes in the lead (3.6-mm-thick) slab to provide rigidity. The plate consisted of square holes 6.3 mm on a side arranged in a square array having a center-to-center hole spacing of 12.1 mm. The filter plate was positioned just above (between collimator and source being

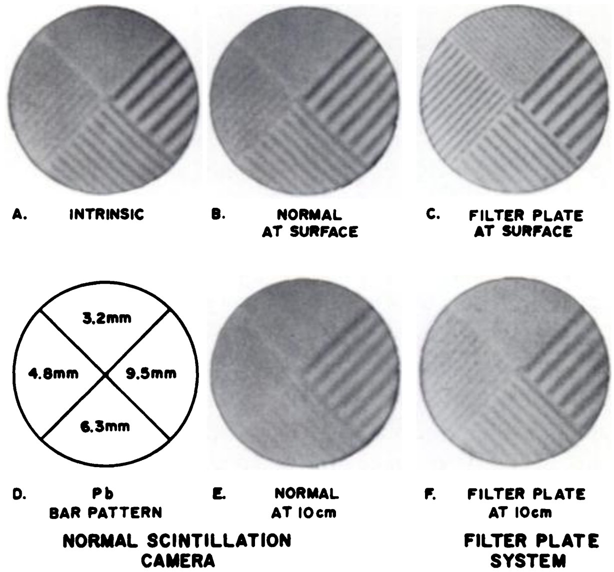

FIG. 4. Lead bar pattern (dimensions are presented at D) placed between system and 38-cm-diam sheet ^{99m}Tc source. A shows intrinsic [graded pattern placed at surface of NaI(Tl) crystal with no collimation] response of normal scintillation camera. B and E show response at surface of high-resolution collimator and at 10 cm, respectively, of normal scintillation camera. C and F show response to same pattern using filter plate system at surface and at 10 cm, respectively. Dimesions of filter holes in plate are presented in text. Relative sensitivity for filter plate is 0.32. Approximately 1,000,000 pulses were collected for each image.

imaged) a Nuclear-Chicago high-resolution collimator insert and was functional in any orientation of the detector head. The use of the high-resolution collimator permitted a direct comparison of filter plate system performance as compared with normal scintillation camera system performance using that collimator.

Resolution was examined with the use of a 38-cm-diam sheet source filled with ^{99m}Tc (typical activities were in the 10–20 mCi range) which transmitted gamma radiation through graded lead bar patterns. The width of the lead bars equaled their separation. The graded pattern was divided into quarters with lead bar widths of 9.5, 6.3, 4.8, and 3.2 mm (i.e., ⅜, ¼, $\frac{3}{16}$, and ⅛ in., respectively) as illustrated at D in Fig. 4. The image at A shows the intrinsic resolution of the scintillation camera. For this measurement the lead pattern was placed at the surface of the NaI(Tl) crystal. Approximately 1,000,000 counts, using a 20% window centered about the 140-keV photopeak, were collected for each of the images shown in Fig. 4.

The images at B and E represent the normal scintillation camera system resolution with the high-resolution collimator, obtained with the graded bar pattern positioned at the collimator surface and at 10 cm from the collimator surface, respectively. The system resolving powers for the filter plate measured with the graded lead pattern at the plate surface and at 10 cm are shown at C and F, respectively.

The sensitivity of the filter plate selected for the present paper was 0.32 relative to the sensitivity of the normal camera using the high-resolution collimator and was measured using the large-diameter ^{99m}Tc source placed at 5 cm from the surface of the system. This sensitivity is in agreement with the computed value. The deadtime of approximately 20 sec associated with moving the filter plate was not incorporated into the above sensitivity measurements since the importance of this deadtime is a function of the total data collection time.

LIMITATIONS

Performance of the filter plate system is limited by sensitivity loss and "ghost" artifacts (defined below). There is a compromise between resolution improvement and sensitivity loss, and clinical evaluation is required to determine an acceptable compromise. "Ghosting" is an artifact generated by imaging a scintillation at a point corresponding to an incorrect (adjacent) filter-hole position. For example, if there exist large nonlinearities in the scintillation camera, the fixed channel bins of the ADC will erroneously assign some of the pulses from a distorted distribution to a digital output corresponding to the central point of a filter hole adjacent to the actual filter hole originating the distribution. Thus, the image of a line source will appear as a line together with a "ghost" line with diminished intensity on either or both sides of the actual position. These artifacts will be displaced from the actual position at a distance corresponding to the center-to-center spacing of the apertures. The limitations that these artifacts present on the usefulness of the system will also require clinical evaluation. Certain alternate approaches are possible, if the problem of "ghost" artifacts proves excessively detrimental to the performance of the system. For example, instead of using the ADC (having preselected fixed "window" positions) to perform the summation upon the signals generated by the camera-filter plate system, a central processing device could be used. The processor could determine the most probable values of the pulse distributions for each filter hole at each data collection point and thus select appropriate regions of summation as a function of distribution shapes determined prior to scanning. A procedure such as this would minimize the effects of ghost artifacts on system performance, and the spatial nonlinearities of the scintillation camera would be improved. However, the large investment necessary to implement such a system makes it desirable to minimize "ghost" artifacts by judicious design of the filter plate.

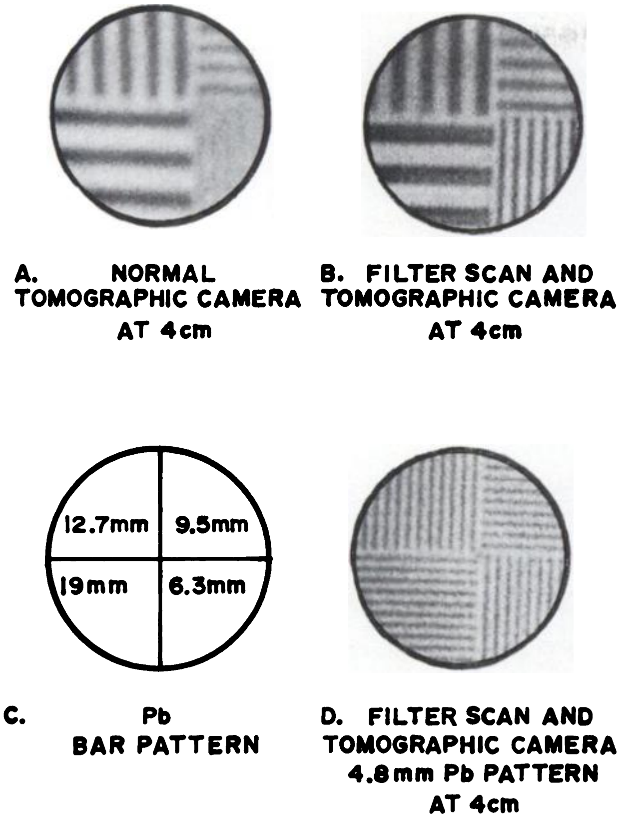

FIG. 5. Lead bar patterns placed between system and ^{99m}Tc sheet source. Dimensions of graded pattern are given at C. Data show comparison of normal tomographic camera and composite system consisting of tomographic camera (with rotating collimator) and movable filter plate. Only images observed in plane of focus are shown. Approximately 400,000 pulses were collected for each image.

Although in the present experiment the filter plate was separate from the collimator, an integrated system (i.e., making the filter plate and collimator a single entity) is possible. This would be attractive at higher gamma-ray energies where the lead collimator septa are visible in the images due to their increased wall thickness. Such a system would remove these septal artifacts. Also the relative sensitivity loss for a high-energy system would be less than for a low-energy system due to the thick septa required for proper collimation at these energies.

Tomographic application. A filter plate system has been adapted to a tomographic scintillation camera using a rotating collimator and table. A tomographic camera of this type has been described by Muehllehner (*8*). For the experiment discussed below the aperture plate was mounted above (between collimator and source) the rotating collimator. The variations in signal levels due to the rotating collimator were electronically removed prior to analysis by the filter system electronics. After analysis by the filter system electronics these variations in signal levels (due to the rotating collimator) were restored electronically, and the signals were then processed by the tomographic system electronics.

Preliminary results using this composite arrangement are shown in Fig. 5. The graded pattern was divided into quarters with bar widths of 19, 12.7, 9.5, and 6.3 mm as illustrated at C in Fig. 5. For the data shown in Fig. 5 the tomographic collimator rotated at a rate of 2 revolutions/min. Data were collected using a ^{99m}Tc sheet source transmitting radiation through the lead patterns. The data shown in Fig. 5 correspond to a photointegration of approximately 400,000 counts for each image. At A the response of the normal tomographic camera to the graded bar pattern placed in the plane of focus and located at 4 cm from the surface of the system is shown. The image at B corresponds to the response of the composite system (tomographic camera and a movable filter-hole plate) to the graded bar pattern positioned as in A. The filter plate consisted of square holes 6.3 mm on a side arranged in a square array having a center-to-center hole spacing of 12.1 mm. Also shown in Fig. 5 at D is the response of the filter scan/tomographic camera system to a uniform 4.8-mm ($\frac{3}{16}$-in.) lead pattern placed in the plane of focus and located at 4 cm. This pattern was not resolvable when placed at 4 cm with the normal tomographic camera system used in the present experiment; thus, the normal tomographic camera response is not shown in Fig. 5.

Thus with this composite arrangement it is possible to resolve the 4.8-mm pattern (placed in the plane of focus) at a distance of 4 cm from the surface of the plate. However, this system was relatively difficult to initialize, and a "beat" artifact appeared on some images due to interference of the two different motions involved. Higher collimator rotation speeds minimized this artifact.

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