COLLIMATOR PERFORMANCE FOR SCINTILLATION CAMERA SYSTEMS

Valerie A. Brookeman and Thomas J. Bauer

Veterans Administration Hospital and University of Florida College of Medicine, Gainesville, Florida

Three Anger camera systems were evaluated for ^{99m}Tc at various source-to-collimator distances in air and water with 3 collimators. Resolution indices and modulation transfer functions improved significantly in some but not all cases with replacement of S-11 phototubes in the Pho/Gamma III camera by bialkali phototubes (resolution indices decreased by 5–32%) and also with modification to the HP camera (resolution indices further decreased by up to 23%). Resolution indices with the 15,000-hole high-sensitivity collimator were larger than those of the 4,000-hole technetium collimator by up to 60%. The 4,000-hole collimator should be used for ^{99m}Tc imaging when better resolution is required for visualization of fine detail and sensitivity is less important. The 15,000-hole collimator offers the best combination of high sensitivity and good resolution at small depths for detection of low count-rate variations in dynamic studies.

Several investigators have reported the characteristics of the Anger scintillation camera including sensitivity, spatial resolution, uniformity, and linearity for various gamma-ray energies and collimators (*1–10*). The number of new camera systems, and new collimators with each camera, recently introduced has greatly increased. We have studied some of those of the Nuclear-Chicago Corporation available to us in our laboratory and report resolution index, modulation transfer function, and plane sensitivity measurements for different collimators which can be used for ^{99m}Tc.

MATERIALS AND METHODS

Systems description. The imaging systems studied were a Pho/Gamma III scintillation camera, initially with conventional S-11 phototubes and later with bialkali phototubes and a Pho/Gamma high-performance (HP) camera. Qualitative estimates of the inherent resolution capabilities of the three cameras are illustrated in Fig. 1. The transmission scintigraphs were recorded without a collimator using ^{57}Co and lead strips with the indicated spacings.

In order to quantitatively evaluate each camera, a PDP-8/I digital computer system with 8K of core memory was used (*11*). Each digitized data image was represented as a 50 × 50 matrix and was corrected for nonuniform sensitivity response of the system by applying a stored digitized matrix of correction factors (*9*). The correction factors were obtained from a crystal flood, the correction factor for any data matrix location being inversely proportional to the flood count for that matrix location.

Three straight-bore collimators were used with each camera—the high-energy iodine collimator, the low-energy technetium collimator, and a new high-sensitivity collimator, with approximately 1,000, 4,000, and 15,000 holes, respectively. The cross sections of the holes of these collimators are circular, square, and approximately triangular, respectively. The physical dimensions of the collimators were accurately measured and are given in Table 1. Because of the circular hole cross section of the 1,000-hole

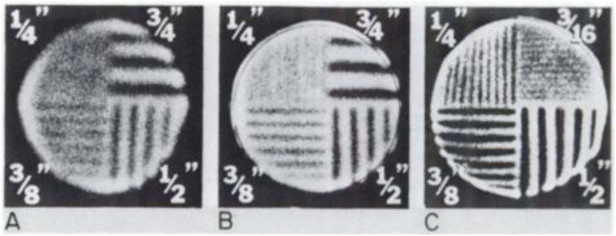

FIG. 1. Transmission scintigraphs recorded with ^{57}Co and lead strip lattice showing inherent resolution of three camera systems. A is Pho/Gamma III camera with S-11 phototubes. B is Pho/Gamma III camera with bialkali phototubes. C is Pho/Gamma HP camera.

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For reprints contact: Valerie A. Brookeman, Dept. of Radiology, The J. Hillis Miller Health Center, University of Florida, Gainesville, Fla. 32601.

TABLE 1. PHYSICAL DIMENSIONS OF STRAIGHT-BORE COLLIMATORS

Collimator	No. of holes	Length (cm)	Septum thickness (mm)	Collimator diameter (cm)	Effective hole diameter, d (cm)
15,000-hole	14,780	1.6	0.1	25.5	0.19
4,000-hole	4,650	4.5	1	27	0.28
1,000-hole	972	7.7	2–4	31	0.60

collimator, the septum thickness ranges from 2 to 4 mm. The noncircular cross section areas A of the holes of the 4,000-hole and 15,000-hole collimators were determined and effective hole diameters d $= [4A/\pi]^{1/2}$ were obtained.

Resolution. All studies were performed with ^{99m}Tc and a 20% photopeak window used routinely in clinical studies.

It is recommended that resolution measurements of imaging systems be performed with line sources of as small diameter as possible, 0.9–1.5 mm being satisfactory (*12*). Plastic surgical tubing of 0.86 mm i.d. was threaded in grooves cut in a 12-in. square Plexiglas base to form three parallel-line sources 5 cm apart which were placed at various source-to-collimator distances in air and with water as an absorbing medium between the line sources and collimator face. A 2-cm air gap was left between the water surface and collimator face. Three million counts were collected by the camera/PDP-8/I. The camera crystal was flooded by placing a 16-in.-diam sheet source of ^{99m}Tc at the face of the appropriate collimator and collecting 3 million computer counts. The correction factors generated were applied to the line-source images collected that day with that collimator to correct for nonuniform sensitivity response.

The resolution index or full width at half maximum (FWHM) of the line-spread function (LSF) was taken as a measure of overall resolution of each camera with each collimator. Measurements of gamma camera LSF's and resolution indices have been shown to be dependent on the orientation of the line source relative to the collimator holes (*7*) and to vary over the detector area (*4,6–8*). Thus the line sources were always positioned under each collimator so that they were not parallel to any rows of collimator holes. The LSF was analyzed at various points along the three parallel line-source images from side to side of the collimator field of view at a total of 17 positions covering the detector area.

The counts between the lines fell to less than 1% of the maximum count at three data matrix locations on either side of the maximum in all cases and thus for each LSF analysis seven data matrix locations

TABLE 2. RESOLUTION INDICES* IN AIR FOR THREE CAMERAS AND THREE STRAIGHT-BORE COLLIMATORS

Source-to-collimator distance (cm)	Pho/Gamma III—S-11 tubes			Pho/Gamma III—bialkali tubes			Pho/Gamma HP		
	15,000-hole	4,000-hole	1,000-hole	15,000-hole	4,000-hole	1,000-hole	15,000-hole	4,000-hole	1,000-hole
1	17.5 (0.5)	16.1 (0.5)	20.4 (2.7)	14.2 (0.4)	12.5 (0.3)	13.9 (0.8)	11.1 (0.7)	9.9 (0.8)	11.4 (1.1)
3	18.5 (0.5)	16.5 (0.5)	20.7 (2.8)						
5	20.1 (0.6)	16.9 (0.3)	21.7 (2.7)	17.4 (0.4)	13.8 (0.4)	15.3 (0.8)	13.4 (0.8)	11.4 (0.7)	13.2 (1.6)
7	23.2 (0.7)	17.9 (0.3)	22.3 (2.5)						
9	24.0 (0.5)	18.5 (0.5)	23.2 (2.0)						
11	27.2 (0.7)	19.2 (0.6)	24.1 (2.5)	23.2 (0.7)	18.2 (0.5)	21.0 (0.6)	17.8 (1.3)	14.2 (0.8)	16.9 (1.0)
21	37.9 (0.9)	23.7 (0.5)	29.1 (1.4)						

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* Mean FWHM values in millimeters with standard deviations in parentheses.

TABLE 3. RESOLUTION INDICES* IN WATER FOR TWO CAMERAS AND THREE STRAIGHT-BORE COLLIMATORS

Source-to-collimator distance (cm)	Pho/Gamma III—bialkali tubes			Pho/Gamma HP		
	15,000-hole	4,000-hole	1,000-hole	15,000-hole	4,000-hole	1,000-hole
2	16.4 (0.5)	13.8 (0.4)	14.4 (0.8)	14.1 (1.0)	11.9 (0.8)	13.8 (1.3)
5	19.9 (0.7)	15.0 (0.4)	16.3 (0.9)	17.0 (1.1)	13.7 (0.7)	16.2 (0.9)
8	24.1 (0.6)	16.5 (0.4)	19.0 (0.5)	19.4 (1.4)	15.2 (0.9)	18.1 (1.0)
10	27.9 (0.6)	17.7 (0.6)	19.7 (0.5)	22.7 (1.9)	17.4 (0.8)	20.7 (1.4)

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* Mean FWHM values in millimeters with standard deviations in parentheses.

were fitted by nonlinear least squares to a Gaussian function with an error mean square of about 0.04. From each LSF, the FWHM and modulation transfer functions, MTF (*12*), were calculated and the mean and standard deviation of the 17 values over the collimator face determined. An IBM-360 computer was used for LSF fitting procedures and determinations of FWHM and MTF values.

The study at 1 cm in air with the camera with bialkali phototubes was repeated with the three line sources rotated 90 deg to check the independence of mean FWHM values with line-source orientation.

Sensitivity. Plane sensitivity was used for the comparison of the cameras with different collimators since it is independent of depth under ideal conditions, which require that the plane source covers the field of view uniformly and that attenuation, penetration, and scatter be negligible (*12*). Since plane sensitivity may be obtained by integrating the line-spread function, a 16-in. calibrated line source was moved at constant speed under the collimated detector by attaching it to the paper of a chart recorder. As the paper moved at constant speed across the collimator face, the line source passed uniformly through the entire field of view. This was repeated with the arrangement rotated 90 deg with two passes of the line source in each orientation and at various depths.

RESULTS

Resolution. Mean FWHM values and standard deviations are given in Tables 2 and 3. The 4,000-hole collimator has superior resolution in all cases and the 15,000-hole collimator shows the fastest deterioration in resolution with source-to-collimator distance because its length is only about one-third that of the 4,000-hole collimator (see Table 1). The individual FWHM values at seven positions across the detector area along the central line source in air at 1 cm are shown in Fig. 2 for the Pho/Gamma III camera with bialkali phototubes and the line sources parallel to the x-axis and then the y-axis. The variations of FWHM over the collimator face were least for the 4,000-hole collimator and greatest for the 1,000-hole collimator. The ranges and standard deviations of FWHM values over the detector area were about 9% and 4%, respectively, of the mean values for the 15,000- and 4,000-hole collimators and about 18% and 8%, respectively, for the 1,000-hole collimator.

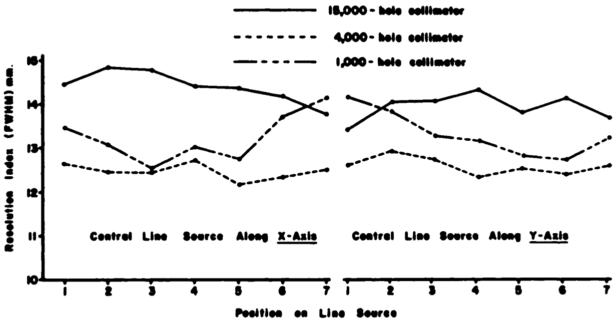

FIG. 2. Resolution indices across collimator face for Pho/Gamma III camera with bialkali phototubes at 1 cm in air for three collimators.

MTF's, calculated from all the LSF's, are too numerous for them all to be illustrated. As examples, Figs. 3 and 4 show mean MTF values at 5 cm from the collimator face in air and with a water absorber, respectively. In these figures, the two standard deviation limits of the determined mean values are shown, enabling intercomparison of cameras and collimators within normal significance limits.

Sensitivity. The results of plane sensitivity meas-

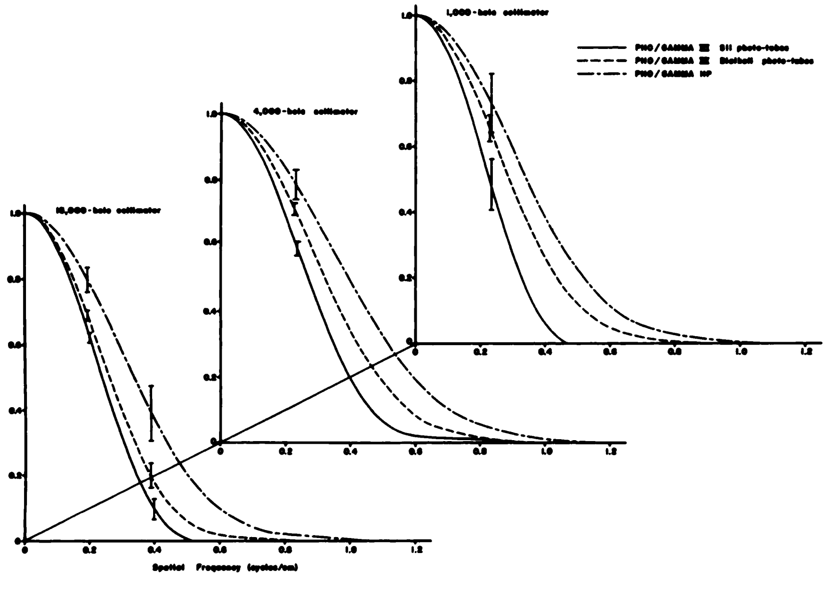

FIG. 3. Mean modulation transfer functions 5 cm from each collimator face in air. Two standard deviation limits are shown (see text).

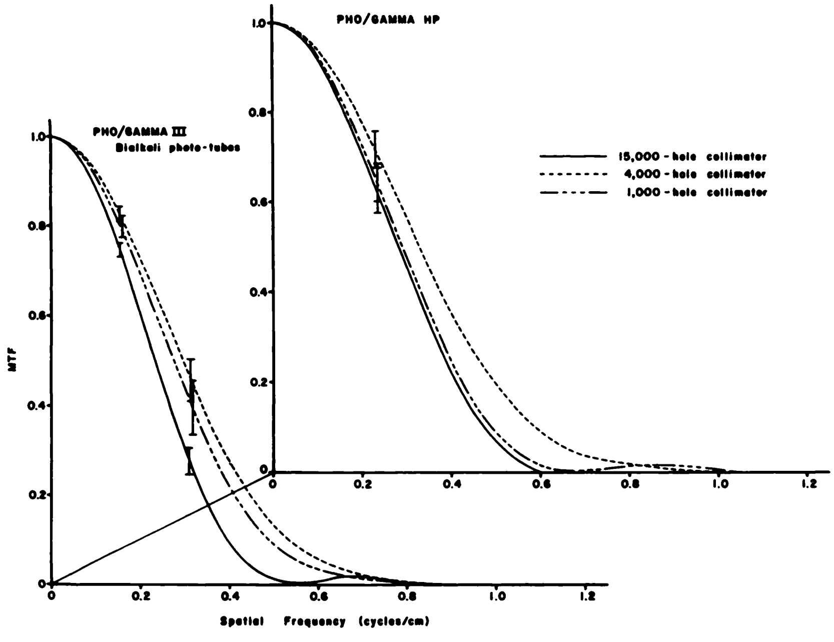

FIG. 4. Mean modulation transfer functions 5 cm from each collimator face with 3 cm water absorber. Two standard deviation limits are shown (see text).

TABLE 4. PLANE SENSITIVITY OF THE PHO/GAMMA III CAMERA WITH BIALKALI PHOTOTUBES

Depth (cm)	Plane sensitivity cpm/(μCi/cm^2)			Sensitivity ratio	
	15,000-hole	4,000-hole	1,000-hole	15,000-hole/4,000-hole	15,000-hole/1,000-hole
0	453	193	175	2.34	2.58
2	457	191	181	2.39	2.53
4	450	195	171	2.31	2.63
10	485	190	174	2.56	2.79
Mean	461	192	175	2.40	2.63
s.d.	16	2	4	0.11	0.11

urements with the Pho/Gamma III camera with bialkali phototubes are given in Table 4. The sensitivity obtained with the 15,000-hole collimator was 2.4 and 2.6 times greater than with the 4,000- and 1,000-hole collimators, respectively. The sensitivities remained fairly constant with source-to-collimator distance indicating minimal attenuation, penetration, and scatter of the ^{99m}Tc 140-keV gamma rays. Sensitivity measurements with the S-11 phototubes camera up to 20 cm gave a mean sensitivity ratio of 2.8 for the 15,000-hole collimator compared to the 4,000-hole collimator which is equal to the ratio obtained with the bialkali phototubes camera within two standard deviation limits.

DISCUSSION

Multiplier phototubes with bialkali photocathodes have 1.5–2 times the quantum efficiency of conventional phototubes with S-11 photocathodes and therefore improve the inherent camera resolution index according to the inverse ratio of the square roots of the quantum efficiencies for the same gamma-ray energy (*13*). The inherent resolution index of the gamma camera with bialkali phototubes is 0.75 times that with S-11 phototubes (*1,2*). Figure 1 shows that inherent camera resolution improved successively with the replacement of the S-11 phototubes by bialkali phototubes and with updating the camera to the HP model. The results in Tables 2 and 3 indicate that with successive camera changes overall system resolution improved, although not always significantly. The standard deviations of mean FWHM values must be considered due to the variation in measured FWHM values across each collimator face. The modulation transfer functions in Figs. 3 and 4 indicate significant improvement with bialkali phototubes and subsequently HP modification.

The largest variations of FWHM values over the detector area occurred with the 1,000-hole collimator and S-11 phototubes camera and the largest change in mean FWHM value on 90-deg line source rotation occurred with the 1,000-hole collimator (Fig. 2). The larger hole diameter and thicker septa of the 1,000-hole collimator make the FWHM values very dependent on line-source orientation relative to the collimator holes. Larsson, et al (7) found variations in FWHM values up to 40% (0.5 cm) for the 1,000-hole collimator at 140-keV energy when a line source was positioned parallel to a row of holes. At small source-to-collimator distances they obtained minimum and maximum resolution indices with the line source directly under a row of holes and lying between two rows of holes, respectively. However, they found no FWHM variations caused by line source position with the 4,000-hole collimator. In our study, 90-deg rotation of the line sources changed the mean FWHM values for the 15,000-, 4,000-, and 1,000-hole collimators by 0.3, 0.2, and 0.6 mm, respectively; less than 1 s.d. in each case (Fig. 2).

Addition of a water absorber did not significantly alter mean resolution indices for the 4,000-hole collimator (Tables 2 and 3), in agreement with others (7). In ^{99m}Tc clinical studies the resolution capabilities of the 15,000-hole high-sensitivity collimator with the bialkali phototubes Pho/Gamma III camera and HP camera may be estimated from Table 3 and Fig. 4, with a water absorber. Overall camera resolution was inferior compared to the other two collimators.

The 15,000-hole collimator studied is more than twice as sensitive as the 4,000-hole collimator. As indicated in Table 1 the collimators have different fields of view. Increasing the diameter of the 15,000-hole collimator by 1.5 cm to equal that of the 4,000-hole collimator would increase the field of view, giving an additional sensitivity gain with no resolution loss for ^{99m}Tc and other low-energy gamma-ray emitters.

As more gamma-camera collimators become commercially available, selection of the best collimator for a particular clinical study will be increasingly difficult. Generally, that collimator which has the greatest sensitivity and the required resolution at the desired depth should be used. The 4,000-hole technetium collimator provides smallest resolution indices and reasonable sensitivity for ^{99m}Tc and should be used with the gamma camera if either better resolution is required for detection of small defects in clinical images or a field of view larger than provided by the 15,000-hole collimator is desired. In dynamic studies it is desirable to record as many counts as possible in small time intervals for greatest statistical accuracy of the resultant transit graphs for small regions of interest. Thus the 15,000-hole collimator should be used for ^{99m}Tc dynamic studies, for detection of small count differences in small time intervals, and in other situations where high sensitivity is required and is more important than spatial resolution.

With the increasing number of different camera systems and new collimators now commercially available and with rapid technical improvements in existing systems, it has become impossible for each individual nuclear medicine laboratory to evaluate the possible gains in sensitivity and resolution or to compare the relative merits of expensive competitive systems. We recommend that similar information and corresponding data to that reported in this paper be provided by the manufacturers for all collimators and camera systems.

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