

New Methods of Examining Gamma Camera Collimators

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New methods are proposed and described to examine the quality of gamma camera collimators in two special performance categories, namely, uniformity in regional efficiency and regional variations in channel tilt. These two performances are critical areas for SPECT imaging. Results obtained from experimental and commercial collimators illustrate the variability seen for these performance characteristics in currently available collimators.

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The basic design of the gamma camera collimator has not changed since it was described by Anger in the 1960s (1). The collimator fabrication techniques have improved over the years to yield better performance. However, the ability of the collimator to meet design specifications has rarely been questioned and investigated. Since a collimator's quality directly affects the quality of the data a camera receives, even a small improvement in collimator performance can result in a significant improvement in overall imaging performance.

New imaging applications such as single photon emission computed tomography (SPECT) place much more stringent demands on camera system performance. The dual requirements of good uniformity and good spatial linearity have been particularly emphasized in SPECT literature (2,3). This new emphasis has prompted the industry to produce for the current market cameras with much improved *intrinsic* uniformity and *intrinsic* spatial linearity. Although these are laudable achievements, we consider them to be only half of the required task in the quest for overall system uniformity and linearity. The other half of the task which has yet to be promoted and accomplished lies in improving the uniformity and linearity of the collimation.

The uniformity, or more appropriately, the nonuniformity of collimation is defined as the regional variation of its photon transmission rates (efficiency) across the collimator core. It is affected mainly by nonuni-

formity of the mechanical components made in the fabrication process, such as the variation in size of individual channels, nonuniformity in the thickness of septa and distortion or damage to septa created during the construction process. For foil collimators, uneven spacing and misalignment of the corrugated strips during assembly can also cause nonuniformity (4).

The linearity of collimation depends on how accurately each channel in a collimator is oriented in line with a predefined direction. The regional channel tilt of a collimator is the average deviation of angular orientations of the individual collimator channels in this region from the intended direction. It has been generally assumed that in a parallel hole collimator, all the channels are perpendicular to the collimator surface. Due to the difficulties encountered in various phases of the fabrication procedures, regional variations of the channel tilt exist and directly lead to projection errors in data sampling (5). Unless these projection errors can be corrected in the image reconstruction phase of SPECT imaging they can lead to significant loss of resolution in the reconstructed images. The regional resolution loss is proportional to the magnitude of the regional channel tilts and the distance between the object of interest and the collimator face. For example, a 1-degree channel tilt can introduce a 3.5 mm error in projection and backprojection at a distance of 20 cm. Under certain situations this error may double to 7 mm when the opposing view is utilized in the image reconstruction.

In this paper we propose new quantitative methods for examining collimator quality with regard to uniformity of efficiency and regional channel tilt. These new performance tests were applied to various com-

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mercial and experimental collimators. The results are presented to illustrate the performance variability we have found for these parameters on recently manufactured collimators. We also present the results of data analysis devised to yield quantitative indices of collimator quality along with qualitative distribution maps of the regional variation in these two performance parameters for selected collimators.

MATERIALS AND METHODS

Collimator Uniformity

A special rectilinear scanner was employed to measure the uniformity of collimators. This scanner is similar to a commercially produced bone-density transmission scanner. The scanner is used to record the regional transmission rate of a radioactive source through a piece of collimator core on a point-by-point basis as a two-dimensional digital image. Our instrument differs from a current commercial transmission scanner only with respect to the collimation of the transmission photon beam. A transmission gamma-ray source is placed in a 10-ml vial behind a 3-mm-thick lead mask that has a 6-mm-diameter circular aperture to create a slightly divergent scanning beam. The scanning beam is aimed at an uncollimated 2-in.-diameter, 1-in.-thick NaI(Tl) crystal detector. Both the detector and the source move in synchrony on parallel planes which closely flank (~1 cm above and 1 cm below) the collimator faces during the scanning motion, so that the transmission beam is at all times perpendicular to the collimator face and intercepted by the detector. The reason that a slightly divergent beam was employed was to reduce the system's sensitivity to small variations of collimator channel tilt. These will be independently analyzed by a different technique (see below). The scanner system is under the control of an IBM-PC. Data are stored on floppy disks and later transmitted to a VAX-based image processing system for display and further analysis.

Scan data were collected every 3 mm in a 64 × 64 square matrix to cover a 19 cm × 19 cm section at the center of the collimator core. We chose to collect data from the center of the collimator, because the scan field size is limited on our current scanner. A mechanical modification of the scanner will allow scanning of the entire collimator in the future. The energy resolution of our detector was determined to be 15% FWHM at 140 keV. Technetium-99m source activity was adjusted at the beginning of a scan to yield a mean transmission rate of about 20 k cts/sec with a 40% window. Count rate data was acquired in discrete steps for 2 sec at each sampling position and decay corrected before recording. The time required to complete the whole scan was nearly 4 hr, due to the limited count rate response of the current detector. The acquired data are displayed as an image depicting regional uniformity in efficiency for the collimator. With appropriate enhancement, small variations in regional transmission rates are readily perceived by visual inspection. Statistical analysis was applied to the recorded data to derive mean and standard deviation values for regional sensitivity. The ratio of the s.d. and the mean, expressed as percent standard deviation (%s.d.), is a global index of the nonuniformity of the collimator.

Channel Tilt

To measure variations in channel tilt, we designed and built a rectilinear holder for a group of point sources as shown in Figure 1. This device consists of a frame with a series of precisely constructed parallel slots designed to hold a tray of point sources at progressively greater distance from the collimator surface of a camera, while maintaining each point source on a single straight line perpendicular to the collimator surface. Guide rails located at the bottom of the tray make the fitting snug and allow no lateral movement.

All the following testing of collimators was done with the collimator mounted on a scintillation camera. The test procedure consists of gamma camera imaging of point sources at different altitudes on top of the collimator being tested. The output image of the camera was digitized and stored in a standard nuclear medicine computer system. When the tray of point sources is moved to a different altitude (i.e., slot at a different height on the holder) any deviation in collimator channel orientation from a line perpendicular to the detector surface will produce a shift in the point source image position proportional to the magnitude of the angular channel tilt from the perpendicular line. The geometric relationships for this determination are shown in Figure 2. The angle of regional tilt of the collimator channels can be calculated as follows.

$$\theta = \tan^{-1} \frac{(\text{magnitude of distance shifted in image plane})}{(\text{change in altitude})}$$

One of the basic assumptions in this calculation is that the channel tilt characteristics of a collimator is a slow changing function with distance. In fact, this test is not designed to detect sharp changes in channel tilt. If there are sharp changes,

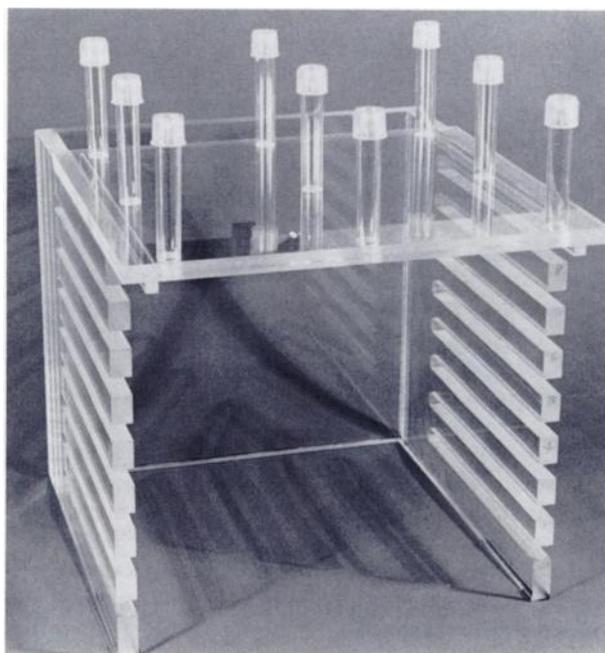


FIGURE 1
A precision rectilinear tray holder with many parallel slots to hold trays at fixed distances from the base. Each of the point sources on the tray remains on the same perpendicular line as the tray moves from slot to slot.

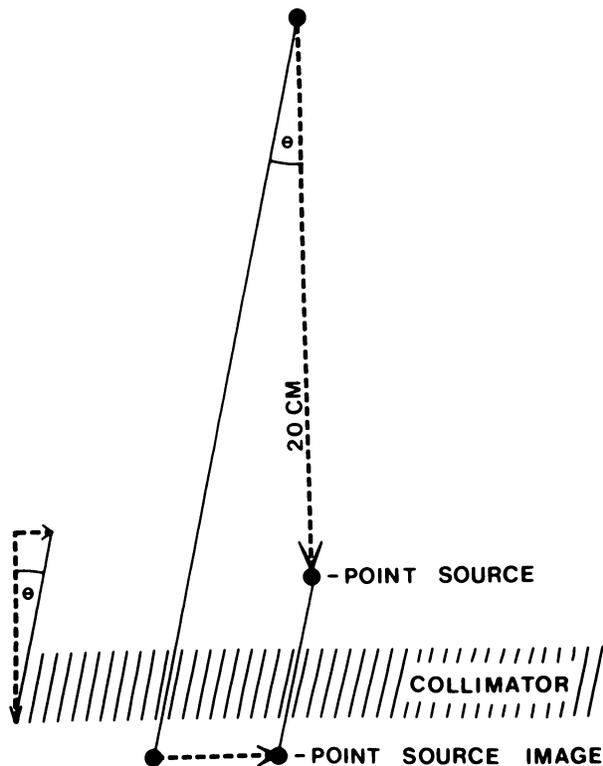


FIGURE 2
The channel tilt angle Θ can be measured by the shift of point source image location caused by the change of altitude of the point source.

we believe the uniformity test would be more sensitive to such irregularities.

To acquire the data needed for this formula, images of extended point sources (1-cc-source volume in a 10-mm-diameter test tube) were acquired on a gamma camera with a 128×128 image matrix. The source tray was imaged at distances of 2.5 cm and 22.5 cm from the collimator face. The x and y coordinates of the center of each extended point source image were computed with the centroid method. The differences between the coordinates of the two point source images representing the point source at the two different altitudes is a measure of the shift observed. Since the shift has both x and y components, it can best be represented as a vector. The magnitude of the shift vector normalized to the change of point source altitude is expressed in units of degrees.

The magnitude and direction of the shift vector can be plotted on a two-dimensional map as an arrow. In our experiments, nine-point sources were placed on the tray to assess nine regions simultaneously. The pattern of point source locations on the tray was in the form of a 3×3 matrix with a 10-cm distance between adjacent sources. The holder was subsequently manually displaced three times to form a 6×6 square grid, so that a total of 36 independent regions of the collimator were examined.

RESULTS

Seven collimators supplied by commercial vendors were subjected to our new performance tests. For this

communication, we have selected data from four commercial and one experimental collimator to illustrate the variety of results obtained for these two newly defined performance categories.

Uniformity

Figure 3A shows the uniformity images of a control scan representing the scan data obtained when no collimator was placed between the source and the detector. It was acquired with the same scanning procedure that was used to test the collimators. This image, in fact, shows the intrinsic uniformity of our rectilinear scanning. The rest of Figure 3 shows the images derived from three different collimators. The observed variation of the transmission rate data is within $\pm 2-5\%$ of the mean value for all the collimators tested. A 10% display window centered at the mean pixel value was adopted to enhance the small regional variations in all the images shown (image contrast is enhanced by a factor of 10). The %s.d. for the control scan is 0.6%, which is very close to the Poisson noise that is expected (0.55%) from the mean counts (32,000) of all the data points. The intrinsic uniformity image of the control scan also reveals a subtle structure pattern which is caused by the imperfect response of our fairly old detector assembly.

The %s.d. of the three collimator images shown are 2.2%, 1.8%, and 1.1%, respectively. After factoring out the contribution caused by the intrinsic uniformity of the rectilinear scanning, following the formula that $s.d._1^2 = s.d._{total}^2 - s.d._2^2$, the net %s.d.s of the uniformities of the three collimators are 2.1%, 1.7%, and 0.9%. Correlation between the %s.d. and the severity of regional variation can be readily appreciated.

The nonuniformities of Collimator A, shown in Figure 3B, represent a worst case example obtained from an experimental collimator sent to us for evaluation by a manufacturer: gross nonuniformity and structure pattern are present along the foil direction. The second example, shown in Figure 3C from a commercial vendor (collimator B), shows the existence of a transmission rate gradient from top to bottom superimposed on a few focal clusters of low transmission areas (dark shades). The third example, collimator C in Figure 3D, shows no sharp changes in the pixel values, though gradual variations of regional transmission rate are recognizable.

Channel Tilt

For the channel tilt test, three sample cases were selected to illustrate the variety of results obtained. The shift vectors, as indicated by arrows, were plotted from the location of the center of the distant point source to the center of the proximal point source. Thus, the direction of the vector indicates the direction of the regional collimator tilt and the magnitude of the vector indicates the severity of the tilt.

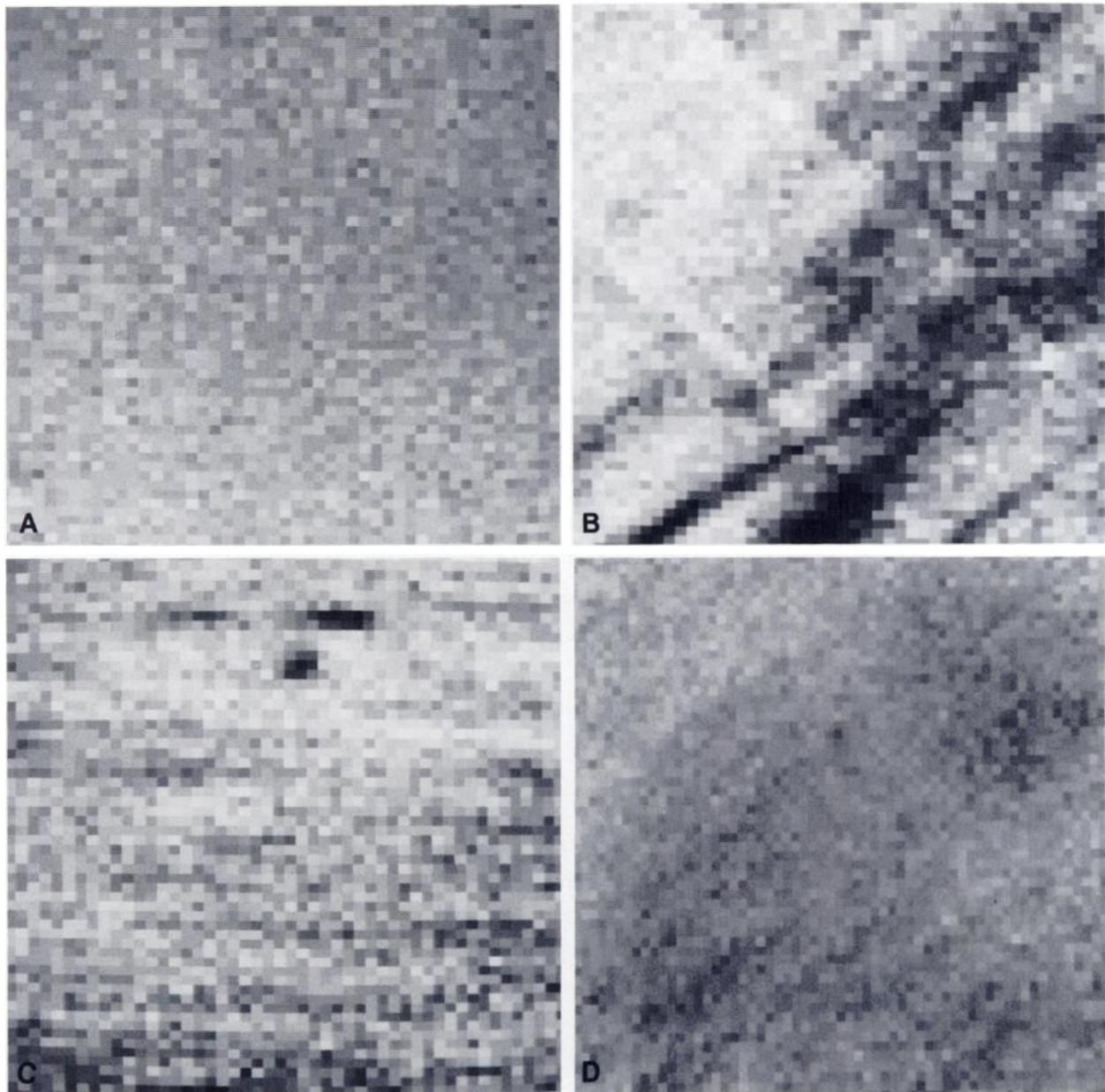


FIGURE 3
The uniformity image of: A: Control scan; B: Collimator A; C: Collimator B; D: Collimator C.

The first vector plot, shown in Figure 4A, is obtained from the same experimental collimator A. Again, this is an extreme case. The second plot, from a commercial collimator D in Figure 4B, shows a similar tilt for all 36 regions. The tilts are all in one direction and of about the same magnitude. This finding indicates this collimator functions as a 1-degree slant-hole collimator. Figure 4C shows the result for collimator E, which turned out to be the best result that we have seen from a commercial collimator in our limited series. Some regional variations of channel tilt exist, but all of the tilt magnitudes are $<0.5^\circ$. The mean and s.d. of the tilt magnitudes for the collimators shown above are calcu-

lated to be: A, $1.08^\circ \pm 0.54^\circ$; D, $0.98^\circ \pm 0.18^\circ$; E, $0.20^\circ \pm 0.12^\circ$.

DISCUSSION

Due to the advances in modern electronics in the last decade, the Anger camera has been constantly refined to yield better intrinsic performance. Among the most important improvements have been those relating to the intrinsic uniformity and intrinsic spatial linearity response of the camera. However, these remarkable improvements have not been fully realized in routine

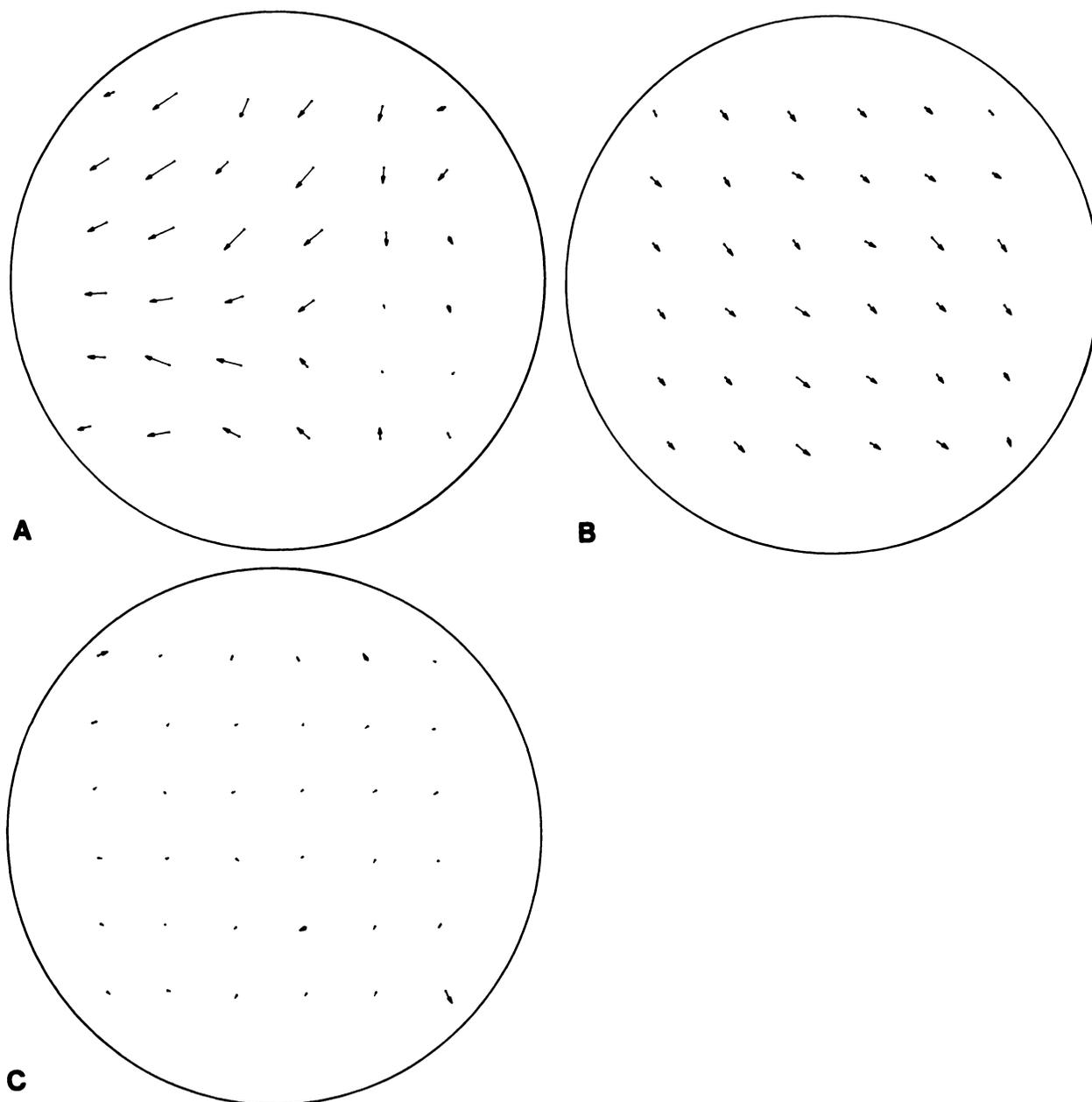


FIGURE 4
 The shift vector map of three collimators: A: Collimator A ($1.08^\circ \pm 0.54^\circ$); B: Collimator D ($0.98^\circ \pm 0.18^\circ$); C: Collimator E ($0.20^\circ \pm 0.12^\circ$). The circle indicates the useful field of view of the collimator.

clinical imaging, which is currently limited not by the intrinsic but mainly by the extrinsic performance of the imaging system. The problem is at the very front-end of the camera imaging system, where the collimator imposes by far the most severe limitations on the overall performance of the Anger camera.

The nonuniform sensitivity of camera system performance has long been an issue in nuclear imaging. Several different approaches have been implemented either prospectively or retrospectively to correct for this problem over the years. Most of the correction schemes also have their associated pitfalls (5). Nonuniform sen-

sitivity response continued to be a problem until the basic causes of the nonuniformity, i.e., spatial nonlinearity and the regional variation of pulse height response, were identified and compensated (7,8). Most of the current state-of-the-art cameras have reasonable intrinsic uniformity in regional sensitivity. Nevertheless, for high count density SPECT applications, it is still generally recommended to have an extrinsic flood correction on the acquired data before tomographic image reconstruction to further reduce the residual intrinsic nonuniformity and the extrinsic nonuniformity introduced by the collimator (2).

This flood correction, however, is no trivial matter. The correction procedure is time consuming, requiring a very uniform flood source, and should be done specifically for each collimator. It should preferably employ the same radionuclide that is used in the clinical imaging for which the flood correction is to be applied. Moreover, a high count density flood acquired with the detector in one position of the rotation arc may not properly correct images acquired with the detector in a different portion of the rotation arc. A small amount of random noise is inevitably introduced in the correction process. It is a fact that the majority of SPECT studies do not involve high count density images. No guidelines have been developed regarding the requirement of flood correction for such routine studies as thallium-201 myocardium imaging and iodine-123 brain imaging. On the other hand, the effect of collimator nonuniformity on the overall system uniformity has often been overlooked. We feel that in many cases flood correction is not worthwhile, if good intrinsic uniformity and collimator uniformity can be assured. Rather than using flood correction on a collimator of mediocre uniformity, it is preferable to have a uniform collimator as the basic hardware solution to this problem. Even for high count density SPECT imaging, software flood correction should be reserved as a secondary, postprocessing remedy.

The question now is how to assure a collimator's uniformity. The conventional way to examine a collimator's uniformity is simply to take a flood image on a gamma camera. The problem with this method is obvious. The collimator's response cannot be isolated from the camera's intrinsic uniformity response. Second, the limited intrinsic resolution of a gamma camera often masks the high-frequency components in the collimator's uniformity response. For example, the flood image recorded with our experimental collimator (collimator A) mounted on the gamma camera shows only a minimal change in the region corresponding to the obvious low transmission area at the bottom of Figure 3B. Another way of visually assessing the collimator uniformity is by taking a radiograph. Although the radiograph has excellent resolution, and can reveal structural abnormalities, quantification of global or regional uniformity is difficult. In contrast, our approach, based on rectilinear scanning, has the advantages of excellent intrinsic uniformity and reasonable high frequency response and also provides quantitative images of the photon transmission efficiency of a collimator.

Analysis of the performance test results for six commercial collimators reveals the maximum observed nonuniformity to be only $\pm 2-4\%$ around the mean. The calculated %s.d. provides a global index of collimator uniformity with respect to efficiency. This index allows us to compare collimators on an objective basis. Analogous to the effects produced by regional variations

in a camera's intrinsic uniformity, high frequency variation in the collimator uniformity causes more serious reconstruction artifacts than low frequency variation. An assessment of the distribution and magnitude of the regional nonuniformities can be derived from the recorded transmission rate image by standard image processing techniques, similar to those established by the NEMA recommendations.

All of the collimators shown above were of the "foil" design. The orientation of the foil strips of the collimator examined can be seen in each image. This observation indicates the variation in uniformity across the foil strips to be significantly more than that along the direction of the foil strips. Therefore, one way to minimize the impact of collimator nonuniformities caused by foil strips on SPECT reconstruction is to have the foil strips aligned in a direction transverse to the axis of detector rotation.

Many nuclear medicine laboratories already have a bone density scanner that could be adapted for the examination of collimator uniformity. What is needed is software to accommodate the display requirements for this application. This option could be provided easily by the scanner manufacturers if enough user interest were generated. It is also possible that for this application, the collimation of the photon beam of the bone-density scanner may need some modification. We opted to use a slightly divergent beam for our transmission scanning, because the transmission rate would otherwise be too sensitive to variations in channel orientation. We feel that we can better assess these with our second test.

The performance characteristics defined by these two tests are not totally independent. Even in our limited survey, a collimator with bad uniformity appeared to have wide variations in channel tilt. This project did not attempt, however, to define an exact interrelationship between our two measures of collimator performance.

The error in our measurement of collimator uniformity is mainly caused by counting statistics and should be $<0.6\%$. Since there were few scatter photons in the spectrum of the collimator scanning situation, a 40% wide window was employed to minimize errors in regional count rates caused by drift in the electronics. When a short half-life radionuclide, such as technetium-99m (^{99m}Tc) is used as the source, cumulative error may be introduced in the portrayal of region transmission rates by slight inaccuracies in the decay corrections caused by uncertainty regarding the precise half life of the nuclide (i.e., 6.00 versus 6.05 hr), minor radionuclide impurities (i.e., molybdenum-99) or deadtime of the system. This is a slowly varying component and probably accounts for the slight variations in background level in our control scan. Nevertheless, long-lived sources such as cobalt-57 or gadolinium-153

would be preferable to ^{99m}Tc for conducting this collimator performance test. We used ^{99m}Tc only because of its easy availability in large and adjustable quantities.

For testing of collimator channel tilt, the precision in determining the point source coordinates is excellent (<0.1 pixel or 0.3 mm). The intrinsic tilt of the holder (i.e., the ability of our holder to allow placement of test sources along straight lines perpendicular to the collimator) was excellent. But this feature is not a critical requirement for the successful application of our method, as long as the intrinsic tilt is small and the tested collimator does not have sharp changes. The magnitude and direction of the intrinsic tilt can be easily measured (see Appendix). By this method, we determined the intrinsic tilt of our source holder to be 0.17° . The error imposed by this imperfection of our source holder was factored out of the shift vectors presented in this report.

The average regional channel tilt for the commercial collimators examined was $\sim 1^\circ$ in magnitude. Although the direction of tilt seemed to be randomly oriented, certain regional patterns were noted.

At our current status of SPECT technology, even small amounts of channel tilt introduce projection error and, consequently, loss of resolution in the image reconstruction. However, there are many other factors yet to be optimized that are responsible for even more severe problems in current SPECT imaging. Additional refinements are still needed to guarantee accuracy in leveling the camera detector head, accuracy in detector rotation, and correct determination of the center of rotation.

This communication documents wide variations of nonuniformity and channel tilt in commercially produced collimators used today. The distribution and severity of both of these uniformity characteristics are mainly determined by the collimator fabrication technique and its quality control. Since several collimators performed reasonably well, it should be technically possible to make high quality collimators with good performance characteristics in both areas. As SPECT reaches the refinement stage, efforts in further improving the fabrication techniques for achieving more uniform collimator responses should be encouraged and promoted. This might best be done by establishing new guidelines (such as NEMA specifications) that include realistic criteria for maximum acceptable variations in collimator uniformity with respect to regional efficiency and channel tilt. At the present stage of collimator manufacturing, we would suggest the following criteria which is realistically achievable today as the tentative guidelines for people in the market for collimators to be used in SPECT: (a) the collimator uniformity image should exhibit $<1\%$ in %s.d. measurement and no apparent structured pattern, and (b) channel tilt be better than $0.25^\circ \pm 0.15^\circ$.

APPENDIX

This section shows how we measure the intrinsic tilt error of the perpendicular lines that was built into the holder and how this error can be factored out of the calculated shift vector of channel tilt to make the measurements relatively independent of how accurately the source holder is made.

As shown in Figure 5, if \vec{A} is the true shift vector of a regional channel tilt and \vec{B} is the tilt error of the source holder (deviation from true perpendicular for the line connecting the two source locations) the measured shift vector is \vec{C} , where $\vec{C} = \vec{A} + \vec{B}$.

If we turn the holder around 180° to face the opposite direction, then the tilt of all the perpendicular lines would be reversed to be represented by $-\vec{B}$. A second measurement would then yield \vec{D} where $\vec{D} = \vec{A} - \vec{B}$. With \vec{C} and \vec{D} known, \vec{A} and \vec{B} can be easily calculated as:

$$\vec{A} = \frac{1}{2} (\vec{C} + \vec{D})$$

$$\vec{B} = \frac{1}{2} (\vec{C} - \vec{D})$$

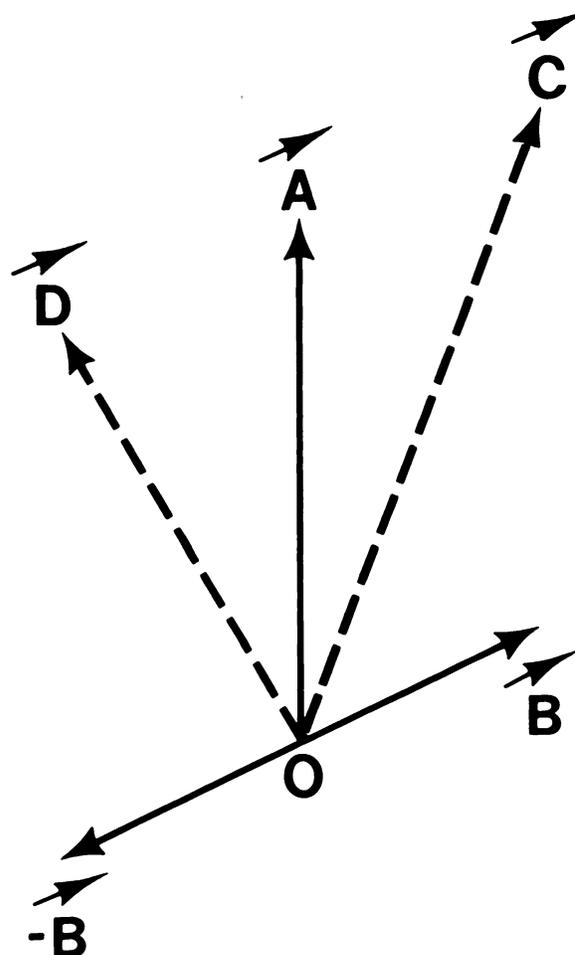


FIGURE 5
 \vec{A} and \vec{B} can be determined from the measurement of \vec{C} and \vec{D} .

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