Optimizing Pinhole and Parallel Hole Collimation for Scintimammography with Compact Pixellated Detectors

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Abstract—The relative advantages of pinhole and parallel hole collimators for scintimammography with compact, pixellated gamma detectors were investigated using analytic models of resolution and sensitivity. Collimator design was studied as follows. A desired object resolution was specified for a pixellated detector with a given crystal size and intrinsic spatial resolution and for a given object-to-collimator distance. Using analytic formulas, pinhole and parallel hole collimator parameters were calculated that satisfy this object resolution with optimal geometric sensitivity. Analyses were performed for 15 cm x 20 cm field of view detectors with crystal elements 1.0, 2.0 and 3.0 mm on a side and 140 keV incident photons. The sensitivity for a given object resolution was greater for pinhole collimation at smaller distances, as expected. The object distance at which the pinhole and parallel hole sensitivity curves cross each other is important. The crossover distances increased with larger crystal size for a constant object resolution and increased as the desired object resolution decreases for a constant crystal size. For example, for 4 mm object resolution these distances were 5.5 cm, 6.5 cm and 8 cm for the 1 mm, 2 mm and 3 mm crystal detectors, respectively. The results suggest a strategy of parallel hole collimation for whole breast imaging and pinhole collimation for imaging focal uptake. This could be accomplished with a dual detector system with a different collimator type on each collimation for whole breast imaging and pinhole collimation for imaging focal uptake. Multiple pinhole collimators have the potential to increase sensitivity yet maintain high image resolution. An experimental SPECT phantom study with a four-pinhole collimator was acquired with a pixellated detector. The iterative maximum-likelihood expectation-maximization (MLEM) reconstruction of a hot sphere in a warm cylinder showed the potential of multipinhole collimation to improve sensitivity for tomographic pinhole scintimammography.

I. INTRODUCTION

Parallel hole collimation [1] and pinhole collimation [2, 3] have been employed for scintimammography with standard gamma cameras. Pinhole collimation with object magnification permits image resolution that is better than the intrinsic resolution of the detector. Sensitivity is improved when the pinhole is moved closer to the object being imaged. Resolution with parallel hole collimation degrades as the source to collimator distance increases, while sensitivity remains approximately constant as a function of distance. Pinhole collimation is generally advantageous for high resolution, high sensitivity imaging of small objects, while parallel hole collimation generally has the sensitivity advantage where resolution requirements are not as stringent.

In this contribution the design of pinhole and parallel hole collimators is investigated as follows. A desired object resolution is specified for a pixellated detector with a given crystal size and intrinsic spatial resolution, and for a given object-to-collimator distance. Then, using analytic formulas, the pinhole and parallel hole collimator parameters are calculated that meet this object resolution with optimal geometric sensitivity. The goal of this analysis is to guide collimator design and selection for clinical studies.

Multipinhole or coded aperture collimators with overlapping or multiplexed projection images have the potential to increase sensitivity yet maintain high image resolution and have been proposed for high resolution, high sensitivity small animal imaging [5-7]. This idea also may have application to breast imaging, which motivated an experimental SPECT acquisition and image reconstruction of a high activity sphere in a lower activity cylinder with a four-pinhole collimator.

II. METHODS

A. Pinhole collimator optimization

Analytic formulas for the resolution and sensitivity of pinhole collimators have been previously developed [8]. Object resolution in the image is given by

$$ R_o = \left( \frac{\theta}{f} \right) \left[ R_D^2 + \left( \frac{\ell + x}{x} \right)^2 d_e^2 \right] $$

(1)

and geometric point sensitivity by

$$ g = d_e^2 \cos^3 \theta / (16 x^2) $$

(2)
with the effective pinhole diameter

\[ d_e = \left\{ d \left( d + \frac{\mu}{2 \tan \theta} \right) \right\}^{1/2} \]  

(3)

Here \( f \) is the focal length, \( x \) is the distance from the pinhole along the central axis of the collimator, \( \theta \) is the raypath angle from the central axis, \( R_D \) is the intrinsic spatial resolution of the detector, \( d \) is the pinhole diameter, \( \mu \) is the attenuation coefficient of the pinhole material and \( \alpha \) is the full acceptance angle of the aperture. When \( x, f \) and \( R_D \) are set, \( d \) can be varied to achieve a particular object resolution \( R_o \), and then the geometric point sensitivity can be computed.

B. Parallel hole collimator optimization

Optimization of sensitivity for a parallel hole collimator for a given object resolution can be performed by the approach of Keller [9] that uses the sensitivity and resolution formulas of Anger [8]. In brief, geometric sensitivity can be expressed by

\[ g = \left( \frac{K d^2}{a_e (d + t)} \right)^2 \]  

(4)

where \( K \) is a collimator hole shape factor, \( d \) is the hole width, \( t \) is the septal thickness, and the effective hole length \( a_e \) is given by

\[ a_e = a - \frac{2}{\mu} \]  

(5)

where \( a \) is the physical hole length and \( \mu \) is the attenuation coefficient of the collimator material.

The object resolution can be expressed by

\[ R_o = \left[ R_D^2 + R_g^2 \right]^{1/2} \]  

(6)

where \( R_D \) is the intrinsic spatial resolution of the detector as for the pinhole camera and the geometric resolution is

\[ R_g = d (a_e + b + c) / a_e \]  

(7)

Here \( b \) is the object to collimator distance and \( c \) is the distance from the end of the collimator to the middle of the scintillation crystal.

The minimal raypath distance in the septa can be written

\[ w = -\frac{\ln \beta}{\mu} \]  

where \( \beta \) is the maximum allowable septal penetration factor. The septal thickness \( t \) then can be approximated by

\[ t = 2dw / (a - w) \]  

(8)

When \( R_o, R_D, b \) and \( c \) are set, equation (5) can be substituted into (4), equation (7) can be solved for \( d \) and substituted into (4) and (8), and then the expression for \( t \) can be substituted into equation (4). The derivative with respect to hole length \( a \) can be taken, which leads to maximal sensitivity when

\[ a = -\frac{\ln \beta}{\mu} + \left\{ 2 \left( \frac{\ln \beta}{\mu} \right)^2 + 4 \ln \beta \right\} / \mu - 2(b + c) \ln \beta / \mu \right\}^{1/2} \]  

(9)

Once this optimal value of \( a \) is known, one can solve for \( a_e \), then \( d, t \) and \( g \).

C. Comparison of pinhole and parallel hole collimation

Calculations were performed for a pixellated detector with a 15 cm x 20 cm field of view and for 140 keV incident photons. For pinhole breast imaging the focal length was chosen with the requirement that the sensitivity 10 cm from the collimator axis for a magnification factor of 1.0 be at least 50% of the sensitivity on the collimator axis. This leads to a minimum focal length of 13.0 cm; at smaller focal lengths the angular dependence of sensitivity (equation (2)) leads to relative sensitivity values of less than one half.

Figure 1. Geometric sensitivity vs. object- collimator distance for pinhole and parallel hole collimators and pixellated detectors with intrinsic spatial resolutions of (a) 1.25 mm, (b) 2.25 mm and (c) 3.25 mm. Legend notation: ph=pinhole, par=parallel hole, followed by the desired object resolution in the image.
Optimized collimator parameters were computed for detectors with crystal elements 1.0, 2.0 and 3.0 mm on a side, 5 mm long and with crystal pitches 1.25, 2.25 and 3.25 mm, respectively.

The effect of the 0.25 mm optical diffusing material between the crystals was included in the sensitivity calculations. Detector resolution was modeled to be the same as the crystal pitch. Results are presented for 3.0 and 4.0 mm object resolutions in the images for object-to-collimator distances between 1 and 10 cm. The pinhole collimator was assumed to be fabricated with an 18.0 g/cm³ tungsten alloy and sensitivities were computed on the collimator axis. The parallel hole collimator was assumed to lead with square holes in a square grid and the allowable septal penetration factor β was 0.05.

D. Multipinhole experiment

The potential use of multipinhole collimation for scintimammography with a compact gamma imager was tested using a pixellated gamma camera with a field of view of 13 cm x 13 cm. The scintillator array was constructed from NaI(Tl) crystals 3.0 mm on a side and 6 mm long (St. Gobain Crystals and Detectors), with a crystal pitch of 3.3 mm. The scintillator array was coupled to a 5 x 5 array of Hamamatsu R7600-00-C8 position-sensitive photomultiplier tubes. The data acquisition system was controlled by an Apple Macintosh G3 workstation with user interface and image display software written using the KMAX development system (Sparrow Inc., Daytona Beach, FL).

Single photon emission computed tomography (SPECT) projection data were acquired for a 1.2 cm diameter sphere filled with Tc-99m in a 10 cm diameter cylinder with a low background activity level. Data were acquired for 100 equally spaced angles over 360 degrees (3.6 degree increment). The pinhole array consisted of a tungsten plate with four 2 mm diameter pinholes located at the corners of a square 1.6 cm on a side. The focal length was 11.3 cm and the distance from the pinhole to the axis of rotation was 11.3 cm. Images were reconstructed using the iterative maximum-likelihood expectation-maximization (MLEM) algorithm [10] adapted for multipinhole image reconstruction.

III. RESULTS

A. Pinhole and parallel hole collimator comparison

Graphs of sensitivity vs. object distance from the pinhole or collimator surface are shown in Figure 1. As expected, sensitivity for a given object resolution is greater for pinhole collimation for smaller object distances. The distance at which the pinhole and parallel hole curves cross each other is important. For 1.25 mm detector resolution this is 5.5 cm for 4 mm object resolution and 6 cm for 3 mm object resolution; for 2.25 mm detector resolution the crossover distance is 6.5 cm for 4 mm object resolution and 8.5 cm for 3 mm object resolution; for 3.25 mm detector resolution the crossover distance is 8 cm for 4 mm object resolution and 3 mm object resolution cannot be achieved with parallel hole collimation. The crossover distances 1) increase with larger crystal size for a constant object resolution and 2) increase as the desired object resolution decreases for a constant crystal size.

For imaging an entire compressed breast (~4-6 cm thick) with good sensitivity near the edge of the field of view, parallel hole collimation usually will be the best option. The front face of the collimator can be placed directly above the compression paddle to minimize the distance between the breast tissue and the collimator. Sensitivity will be much better than can be achieved with a pinhole collimator whose aperture must be placed a greater distance from the breast in order to image the entire breast in the field of view of the detector. On the other hand, for imaging suspicious activity uptake in just part of the breast, the pinhole can be brought close to the breast and greater sensitivity can be achieved than with parallel hole collimation.

The above results provide a strategy for the efficient use of compact pixellated detectors for scintimammography: parallel hole collimation for whole breast imaging and pinhole collimation for high resolution, high sensitivity imaging of anomalous activity regions. This could be accomplished with a dual detector system with a different type of collimator on each head or with a single head system with a rapid collimator switching mechanism.

This comparison of parallel hole and pinhole collimators has been made using only analytic formulas. A more comprehensive analysis would include simulation of SPECT acquisition, image reconstruction and an investigation of contrast and signal-to-noise tradeoffs for different lesion sizes and tumor: background activity concentration ratios.

B. Multipinhole experiment

Projection data and an image reconstruction are displayed in Figure 2. The activity of the single sphere is successfully reconstructed. This experiment shows that multipinhole collimation has the potential to improve sensitivity for pinhole imaging, which may be useful for tomographic scintimammography. A more comprehensive analysis is desirable, with attention to activity outside the field of view of the detector that may hinder accurate image reconstruction, quantitation and lesion detection.

IV. CONCLUSIONS

The relative advantages of pinhole and parallel hole collimators for scintimammography with compact, pixellated gamma detectors were investigated using analytic formulas for resolution and sensitivity. For a 15 cm x 20 cm field of gamma camera with pixellated scintillators having crystals 1-3 mm on a side, sensitivity for a given object resolution was greater for pinhole collimation at smaller distances, as expected. The crossover distances between the pinhole and parallel hole sensitivity curves increased with larger crystal.
size for a constant object resolution and increased as the desired object resolution decreases for a constant crystal size. The results suggest a strategy of parallel hole collimation for whole breast imaging and pinhole collimation for imaging focal uptake. Multipinhole collimators have the potential to increase sensitivity yet maintain high image resolution. The successful iterative MLEM reconstruction of an experimental SPECT phantom study of a hot sphere in a warm cylinder imaged with a four-pinhole collimator and a compact pixellated detector shows the potential of multipinhole collimation to improve sensitivity for tomographic pinhole scintimammography.

V. REFERENCES


