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Effect of pinhole shape on projection resolution

LC Johnson¹, SC Moore², and SD Metzler¹

¹Department of Radiology, University of Pennsylvania, Philadelphia, PA, USA

²Department of Radiology, Brigham and Women's Hospital and Harvard Medical School, Boston, MA, USA

Abstract

We are designing a dual-resolution pre-clinical SPECT system based on square-pinhole apertures for use in applications with a small field-of-view (FOV), such as cardiac imaging of mice. Square pinholes allow for increased sensitivity due to more efficient tiling on the detector compared to circular pinholes. Aperture fabrication techniques cannot produce a perfect square, giving the square pinholes some amount of roundedness at the corners. This work investigates how this roundedness affects the physical properties of projection images in terms of spatial resolution. Different pinhole full-acceptance angles and roundedness values were simulated. To facilitate a fair comparison, properties of the non-square pinholes were manipulated to yield pinholes with approximately the same sensitivity (to within 0.1%) and FOV (to within 0.5%) as those of the square pinholes, subsequently referred to as matched apertures. The aperture size (flat-to-flat edge length) of each non-square aperture was increased until its sensitivity was approximately equal to that of the square pinhole. Next, the full acceptance angle was increased until the FOV of each non-square aperture was approximately equivalent to that of the square pinhole. Sensitivity was calculated to include both the geometric and penetrative sensitivity of a point source, as well as the packing fraction of the multi-pinhole collimator. Using the sensitivity-matched and FOV-matched apertures, spatial resolution was estimated. For the 0.3-mm, 0.5-mm, and 1-mm edge-length square apertures studied, the full-width at half-maximum widened as pinhole shape changed from square to circle, while full-width tenth-maximum showed little change. These results indicate that a perfect square pinhole shape is more desirable than a rounded-square pinhole with regard to spatial resolution when sensitivity and FOV-matched pinholes are compared.

Keywords

Instrumentation; Pinhole Collimation; Simulation; Small Animal Imaging; SPECT; Square Pinholes

1. Introduction

The type of collimation in a SPECT system plays an important role in image quality. Currently, most systems utilize pinholes with a circular aperture shape in small-animal systems (Peterson and Shokouhi, 2012). This allows for less complicated fabrication, but does not efficiently utilize the detector space of commonly available rectangular detectors due to the inability to closely tile circular projections. Circular pinholes can fill a maximum of ~90% of the detector when packed hexagonally, while square or rectangular projection

shapes have the potential to fill up to 100% of the detector. Some systems have been developed that increase detector utilization by altering the projection shape. Square or rectangular projections have been made by inserting additional shielding between the collimator and detector to both reduce multiplexing and change the projection shape (Beekman *et al.*, 2005; van der Have *et al.*, 2009). Another method of achieving this is to utilize a loft-hole collimator, which has a circular pinhole but a rectangular entrance/exit opening to change the projection shape (Deprez *et al.*, 2013).

To our knowledge, Zheng *et al.* demonstrated the first documented use of square pinholes (Zheng *et al.*, 2007). They manufactured square pinholes with 0.5, 0.75 and 1-mm aperture edge-lengths using tungsten-epoxy, and their work investigated the benefits of multiple square pinholes with small acceptance angles for fully sampling object space to improve image quality.

We are working to design a system that uses square pinholes in place of loft-hole or additional collimation to better utilize detector area. The system has a dual-resolution collimator tube with two distinct sections, one with a larger diameter tube used for scout imaging followed by a second section where the tube has a smaller diameter in addition to having smaller pinhole diameters used for high-resolution imaging. The intended application of this system is cardiac imaging (Metzler *et al.*, 2012). Given the collimator manufacturing process, it is impossible to produce square-pinhole apertures with perfectly square corners. In previous work (Xia *et al.*, 2013), we have photographed under a microscope manufactured pinholes based on a square design, an example of which is shown in figure 1.

Given that some amount of roundedness is unavoidable, this work aims to determine through simulation whether there is an advantage to using an aperture with a specific degree of roundedness at the corners. We frame the comparison between the square pinholes and pinholes with varying roundedness, by manipulating the physical properties of the non-square pinholes in order to match the sensitivity and field-of-view (FOV) of the rounded-square pinholes to that of the square. To do this, the aperture size (flat-to-flat edge length) of each non-square aperture was increased until its sensitivity was approximately equal to that of the square pinhole. Next, the full acceptance angle was increased until the FOV each of non-square aperture was approximately equivalent to that of the square pinhole. An estimate of the packing fraction was incorporated into the sensitivity. Finally, the spatial resolution of the each FOV-matched and sensitivity-matched aperture was estimated to determine the effect of pinhole shape on the projection.

2. Methods

2.1. Aperture Geometry

A rounded square can be defined as a square whose corners have been replaced with a 90° arc of a circle having a specified radius r . For a rounded-square pinhole, the edge length, w , is defined as the flat-to-flat distance across the center of the shape, as seen in figure 2. The roundedness can then be defined as $2r/w$, which has a range of $[0, 1]$, where 0 is a square and 1 is a circle.

In this study, the aperture walls are designed such that the rounded-square shape is maintained (same radius to edge length ratio) throughout the aperture thickness. Figure 3 shows a schematic profile of the pinhole through its center at an arbitrary acceptance angle and a contour plot of a pinhole in different planes parallel to the aperture from the aperture plane to the upper edge of an aperture with a 50° acceptance angle (α).

We investigate here the optimal roundedness of corners in square-aperture pinholes. To establish a reasonable basis for comparing projection resolution at different degrees of roundedness, we match the FOV and sensitivity to that of the corresponding square aperture by varying the aperture values of acceptance angle and edge length. First, we determine the FOV of the square aperture, and then vary the acceptance angle of apertures with different roundedness until the FOV matches that of the square. Next, we determined the sensitivity of the square aperture and then varied the edge-length of apertures with different roundedness until the sensitivity matched that of the square pinhole. The impact of packing fraction was included in the sensitivity determination. Finally, we determined the resulting projection resolution of the FOV-matched and sensitivity-matched apertures to allow for assessment of optimal roundedness. We investigated five different pinhole full acceptance angles (10°, 20°, 30°, 40°, 50°) and 11 different roundedness values (0, 0.1, 0.2, ... 1) for three different edge-lengths (0.3, 0.5 and 1.0 mm).

For all studies, the SPECT system was configured such that the center of the FOV was 25 mm from the aperture plane of the pinhole collimator and, when applicable, the system magnification was 4.0. This configuration can be seen in figure 4. These values were chosen to approximate the square-pinhole system we are currently designing (Metzler *et al.*, 2012), but our results are nearly independent of magnification since we compared projections on the detector surface. No detector resolution was modeled; hence the term detector pixel size is used to describe the simulated or virtual pixel size.

2.2. FOV and Sensitivity Matching

2.2.1. FOV Matching—The aperture FOV is determined by the pinhole shape and acceptance angle. First, the FOV was estimated using the normalized solid angle for each acceptance angle for a square pinhole (0 roundedness) for the given edge length (0.3, 0.5, and 1.0 mm). Then for each roundedness value, the FOV was estimated and compared to the FOV of the square pinhole. The acceptance angle at this roundedness value was subsequently modified until the FOV was within 0.5% of that of the square pinhole.

We define the aperture FOV to be solid angle of the pinhole through which photons from the imaging plane can enter the detector without interacting in the collimator. To estimate each FOV, we simulated a sheet of activity placed 25 mm from the collimator, i.e., through the center of the phantom shown in figure 4. A collimator thickness extended infinitely away from the source (i.e. $T_L \rightarrow \infty$) was simulated. The sheet was 28 mm $\times$ 28 mm and had pixel sizes of 0.008 mm $\times$ 0.008 mm. From each pixel of the sheet, a photon was emitted towards the exact center of the pinhole. If the line defining this photon's trajectory did not intersect any of the surfaces that define the volume of the collimator material, then the normalized solid angle (NSA) of the pixel was added to the summed NSA, and used as a metric to estimate the pinhole FOV. NSA was calculated as in equation (1), where A is the area of a

pixel, $\vec{r}$ is the vector from the pixel to the center of the pinhole, is the normal to both the aperture and the imaging plane.

$$\text{NSA} = \frac{A}{4\pi|\vec{r}|^3} (\vec{r} \cdot \hat{z}) \quad (1)$$

No penetration was included in this calculation. The summed NSA was subsequently used as a metric to adjust the acceptance angle of the pinholes with different roundedness to match each aperture's summed NSA to that of the square aperture. Using a collimator of extended thickness and forcing photons to pass through the exact center of the aperture makes the FOV independent of the aperture size.

2.2.2. Sensitivity Matching—Using the newly determined FOV-matched acceptance angle determined from the summed NSA, the total sensitivity was estimated for each roundedness value. The total sensitivity was determined by calculating the packing fraction and multiplying it by the pinhole sensitivity. The pinhole edge length was varied until the total sensitivity for each roundedness value approached that of the square pinhole.

2.2.2.1. Single-Pinhole Sensitivity: To estimate each single-pinhole sensitivity value, a simulated single point source was placed 25 mm from the center of the pinhole. The pinhole aperture was assigned the attenuation of tungsten at 140 keV (3.64 mm^{-1}), was 20 mm thick ($T_L = T_U = 10 \text{ mm}$), and was initially simulated for one of the three edge lengths investigated (0.3, 0.5, and 1.0 mm). A virtual detector was placed on the pinhole plane having a grid of 500×500 pixels of $0.005 \text{ mm} \times 0.005 \text{ mm}$. Photons were generated originating from the point source and passing through each virtual detector pixel. Penetration was included by calculating the length of the photon path that passes through the collimator material and using this to determine the attenuation for each point-source to virtual-detector pixel path. The remaining activity fractions from each path were summed to estimate the single-pinhole sensitivity. This method essentially calculates the fraction of photons emitted from the point source that would pass through the collimator. Both geometric and penetrative sensitivity were included in the sensitivity calculation, while the intrinsic detector resolution was not included.

2.2.2.2. Packing Fraction: A perfect square would allow for a packing fraction of one, where all of a square detector is utilized by the projections, while the maximum packing fraction possible for a circle, using a hexagonal packing pattern, is ~ 0.907 . The packing fraction was estimated for the matched acceptance angle determined in 2.2.1 and the given edge length.

We used a Monte-Carlo simulation to distribute activity within a small animal-sized cylindrical object. 47 million photon origins were generated over a cylinder with a length of 40 mm and a diameter of 25 mm as shown in figure 4. They were projected onto the detector using the same method as described in the sensitivity estimation section (section 2.2.2.1). The distance from the detector to the collimator plane was 100 mm, while the distance from the center of the object to the collimator plane was 25 mm, giving a magnification of 4. To

limit simulation time, for each pinhole and acceptance angle combination, the detector's virtual pixel size was determined such that the projection fit into 400×400 pixels, and ranged from 0.46 to 0.08 mm for the 1-mm aperture. Detector intrinsic resolution was not modeled.

After projection images were generated, the resulting images were analyzed to determine the shape of the projection, which was subsequently used to determine the packing fraction. The projection image was assumed to have a rounded-rectangle shape as in figure 2. Each projection was masked to include only counts above 10% of its maximum, and the lengths of the projection at 0, 45, and 90 degrees were estimated. These values were then used to estimate the x and y edge length and the radius (r) of the projection. After these were determined, they were used to estimate a packing fraction based on a hexagonal packing pattern, examples of which are shown in figure 5. The packing fraction was calculated as the sum of the area of the seven hexagonally-placed pinhole projections falling within the central hexagon divided by the area of the large central hexagon.

2.2.2.3. Total Sensitivity Matching: Total sensitivity is defined as the single-pinhole sensitivity multiplied by the packing fraction. The total sensitivity of the square pinhole with a given edge length was first estimated. Next, the edge lengths of pinholes with non-square roundedness were varied until the total sensitivity was within 0.1% of the original square pinhole edge length and acceptance angle. As each edge length was varied, the radius was also adjusted to maintain the same roundedness value.

Because the edge length is used to determine the packing fraction, the total sensitivity-matched result requires an iterative process. An estimate of the packing fraction based on the results from a single-pinhole sensitivity-matched simulation was used as a starting point, and the single-pinhole and packing fraction match was iterated until the edge length, and subsequently the total sensitivity, became stable. This required three iterations.

2.3. Resolution Comparison

After determination of each new acceptance angle and edge length, a single-point of activity 25 mm from the center of the pinhole was simulated for each aperture using the same method as the sensitivity estimation (section 2.2.2.1) with the detector located 100 mm from the pinhole plane. The resulting projections, an example of which is shown in Figure 6 (a), were used to estimate the spatial resolution. For each projection, profiles were formed along directions described by angles from 0 to 45 degrees with respect to the flat-to-flat direction by summing along the perpendicular direction. This is equivalent to calculating the Radon transform. The resulting summed line profile, five of which are shown in Figure 6 (b), was then used to determine the full width at half maximum (FWHM) and tenth maximum (FWTM) at that angle. Figure 6 (c) shows the resulting FWHM and FWTM determined from the summed line profile at every measured angle. The geometric mean of the FWHM and FWTM values across all angles, i.e. the lines in Figure 6 (c), was calculated and used as an estimate of spatial resolution.

3. Results

3.1. FOV and Sensitivity Matching

3.1.1. Matched α —The summed NSA of the perfect-square pinhole, used as a FOV metric, was estimated to be 0.0024, 0.0096, 0.021, 0.037, and 0.057 for the 10°, 20°, 30°, 40°, and 50° full acceptance angles (α), respectively for the case of the 1.0-mm starting edge-length. The resulting acceptance angles that match this FOV metric are shown in figure 7.

3.1.2. Total Sensitivity—The total sensitivity was determined from the sensitivity of a single pinhole and the packing fraction. The packing fractions used in the final iteration for each edge length are shown in figure 8. As expected, the packing fraction values decreased as the roundedness increased. The theoretical curve in figure 8 was determined by calculating the packing fraction when the edge length was fixed to the starting edge length (0.3, 0.5, and 1.0 mm) and the radius was varied to achieve the desired roundedness. Therefore, the theoretical curve represents the packing fraction of a projection having an exact rounded-square shape with no penetration. Figure 9 shows the resulting sensitivity-matched edge lengths, which were matched to the product of packing fraction and aperture sensitivity. The theoretical curves plotted were determined by finding an edge length that matched the area of the square pinhole, and did not consider packing fraction. For all cases, edge lengths larger than the theoretical value were required to compensate for the loss of sensitivity arising from the packing-fraction effect. The total sensitivity values for the 10°, 20°, 30°, 40°, and 50° acceptance angles used for the 1-mm edge length matching were 1.31×10^{-4} , 1.39×10^{-4} , 1.46×10^{-4} , 1.54×10^{-4} , and 1.63×10^{-4} , respectively. Figure 10 shows the ratio of penetrative to total sensitivity for all edge lengths, demonstrating that the ratio is independent of roundedness.

3.2. Resolution Comparison

The resulting opening angles and edge lengths were used to estimate the spatial resolution of the pinholes. Figure 11 shows the resulting FWHM (a,b,c) and FWTM (d,e,f) for the 0.3-mm, 0.5-mm, and 1-mm edge lengths, respectively. The FWHM results show that when the roundedness is increased (i.e., the shape becomes more circle-like), the spatial resolution worsens. For the FWTM, results indicate that there is little change in the resolution as roundedness increases. This indicates that in the tested configurations, the resolution is better for the more square-like shapes.

4. Discussion

Figure 7 shows that acceptance angle increases with roundedness when the FOV is matched. This trend is expected as larger roundedness decreases the FOV due to decreasing the pinhole area and subsequently requires a larger acceptance angle to compensate. The methods used to determine the summed NSA did take into account the pinhole size, but as seen in figure 7 the pinhole sizes tested in this work were not large enough to cause differences in the matched acceptance angles. Figure 8 demonstrates that for all edge lengths investigated, the packing fraction is less than the theoretical curve but fairly close. This

implies that packing fraction worsens when the effects of penetration are included when estimating projection size.

In Figure 9, the theoretical curve did not include the packing-fraction effect when its edge length was estimated, while the rest of the curves show the edge length needed to obtain the total sensitivity, which includes packing fraction. Deviations above the theoretical curve indicate the need to increase the pinhole size disproportionately for the more circular apertures. Figure 10 demonstrates that the ratio of penetrative to total sensitivity is independent of roundedness. As expected, this ratio increases as acceptance angle increases due to the shorter path lengths through the aperture which increases penetration.

Figure 11 demonstrates that when pinholes of varying roundedness are sensitivity-matched and FOV-matched to a perfect square, the perfect square shape has the best FWHM for all acceptance angles investigated. For example, for the 0.3 mm edge-length aperture with an acceptance angle of 10° , the FWHMs were 0.364, 0.387, and 0.414 mm for roundedness values of 0 (square), 0.5, and 1 (circle), respectively.

As many different detector types, and therefore values of detector intrinsic resolution, are available, we chose to present data without modeling detector resolution effects in these simulations. As the total resolution is simply a convolution of the resulting simulation and the detector resolution, detector modeling is not required for this work's goal of understanding the pinhole shape's effect on projection resolution. Additionally, detector-resolution effects have no impact on the FOV or sensitivity matching. Therefore, although the results shown in figure 11 did not include intrinsic detector resolution, the trends shown would remain the same while the overall resolution values would worsen.

Increasing acceptance angle increases pinhole penetration, and subsequently increases its effective diameter. In the case of a circular pinhole with truncated projections (made from additional shielding, e.g. baffles), the circular projections would need an increased acceptance angle to fully fill the FOV of the additional non-circular shielding. This increase in acceptance angle would increase the amount of penetration, thereby making it harder to achieve smaller effective apertures, which would subsequently worsen resolution. Therefore, it may be beneficial for systems requiring high-resolution to utilize square pinholes as opposed to circular pinholes with truncated projections.

Although this work focuses on square apertures to allow for more straightforward comparisons, the effects of roundedness on rectangular apertures should be similar. Rectangular projection shape can be achieved by either using a rectangular-pinhole shape, or by having different acceptance angles along the different square edges. These rectangular shapes could help improve the tiling or packing fraction for multi-pinhole collimators onto rectangular detectors in addition to having independent axial and trans-axial FOV and resolution.

5. Conclusions

Pinhole shape influences both the spatial resolution and the obtainable packing fraction of a system. Understanding these influences is critical to designing a small-animal system that

focuses on applications with a small FOV, as both spatial resolution and total system sensitivity are of critical importance. This work shows that, for the configurations investigated, minimizing roundedness provides better spatial resolution. This implies that precise manufacturing of pinholes should be pursued in order to obtain pinholes with edges as sharp as reasonably achievable since the optimal pinhole shape would be a perfect square.

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Figure 1. Photograph of a square-pinhole designed with a 300 μm edge length and fabricated from a platinum-iridium (Pt/Ir) alloy. The roundedness of the corners of the pinhole is clearly visible.

Figure 2.
Diagram of a rounded-square aperture indicating the edge length, w , and radius, r .

Figure 3.

(a) shows the configuration of the rounded-square pinhole, where α is the full acceptance angle, T_U and T_L are the upper and lower aperture thicknesses, respectively, and w is the edge length. (b) shows the contour of the pinhole with respect to the elevation above the aperture plane, and demonstrates how the aperture maintains its shape at different elevation distances, with z indicating the distance above the pinhole.

Figure 4. Simulated system configuration with mouse-sized cylinder centered at 25 mm away from the pinhole collimator.

Figure 5. Two examples of hexagonal packing structure of rounded-squares, with (a) having almost square and (b) having almost circular pinholes. The packing fraction is the ratio of the unshaded hexagon region to the large, central hexagon's total area.

Figure 6.

(a) An example projection with 0.5 roundedness demonstrating a single angle at which the summed line profile was computed, (b) the resulting summed profiles at 5 selected angles, and (c) the results of the FWHM and FWTM computed for angles between 0° and 45° .

Figure 7.

Full acceptance angle (α) for each roundedness value with a FOV matched to the square pinhole for the 0.3, 0.5 and 1-mm edge lengths are shown in (a), (b), and (c) respectively. As expected, larger acceptance angles are required for greater degrees of roundedness.

Figure 8.

Final packing fractions used to estimate the total sensitivity for determining the matched edge lengths (w) for the (a) 0.3-mm, (b) 0.5-mm, and (c) 0.1-mm edge-length cases for each combination of α and roundedness.

Figure 9.

The sensitivity-matched edge lengths (w) for (a) the 0.3-mm, (b) 0.5-mm, and (c) 1.0-mm starting edge lengths for each given combination of α and roundedness.

Figure 10.

Ratio of penetrative sensitivity to total sensitivity versus roundedness for the 0.3-mm (a), 0.5-mm (b), and 1.0-mm (c) edge length.

Figure 11.

Resolution, measured as FWHM (a, b, c) and FWTM (d, e, f), of the resulting FOV and sensitivity-matched pinhole collimators for the 0.3-mm, 0.5-mm, and 1.0-mm edge lengths, respectively. The FWHM results indicate increasing roundedness worsens resolution, while FWTM remains relatively stable as roundedness increases.