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Slit-Slat and Multislit-Slat Collimator Design and Experimentally Acquired Phantom Images from a Rotating Prototype

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Abstract

We have previously found and validated expressions for slit-slat (SS) geometric efficiency and resolution. These expressions have suggested that SS may be a good choice for imaging mid-size objects or objects that are long axially since (i) the geometric efficiency increases near the slit as h^{-1} (instead of h^{-2} for pinhole (PIN) and either decreases near the collimator for fan-beam (FB) or remains constant for parallel-beam (PB)), where h is the distance from a point to the slit plane; (ii) the transverse resolution is comparable to that of PIN, which is better than that of FB and PB for small objects; (iii) the axial resolution is worse than that of PIN since there is no axial magnification; (iv) there is a large axial FOV, unlike PIN, which is likely to be useful when imaging mid-size or long objects; and (v) there is no need for 3D orbits (e.g., helical) since each slice is complete (like PB and FB).

We have developed a rotating prototype SS collimator that is capable of single-slit or multi-slit acquisition of data. The focal length (FL) is shorter than that of a typical PIN since increasing the FL requires taller slats to maintain resolution; taller slats reduce geometric efficiency. A lead rectangular box was used to provide support and shielding around the slit-slat collimator. Lead slats, spaced with Rohacell foam, were mounted in an assembly with 3 mm pitch.

We have performed preliminary characterization with point sources and acquired micro hot- and cold-rod phantoms and a Deluxe Jaszczak phantom. The projections have been reconstructed using an MLEM algorithm and show good resolution.

Comparisons indicate that SS is more sensitive than PB and FB for the same resolution for smaller-diameter objects. The advantage of SS over PB and FB increases as the desired resolution improves. SS can also be used in configurations that yield projections that have non-isotropic resolution; it is possible for SS to achieve transverse resolutions that are unreachable by PB, since PB does not magnify, and by FB, since its magnification factor for small objects is much smaller than that of SS. Experimental results show that the resolution of the reconstructed phantoms is consistent with theoretical expectations.

Index Terms

instrumentation; SPECT; collimator; fan-beam; parallel-beam; pinhole; slit-slat

I. Introduction

Slit-slat collimation has existed since SPRINT was constructed in the early 1980's [1]–[3]. Recently, this collimator has been re-evaluated, especially for small-animal imaging [4], [5] and for human cardiac imaging [6]. Recent efforts by our group using a stationary prototype have shown that this collimator can be well characterized as a combination of a pinhole collimator in the transverse direction and a parallel-beam collimator in the axial direction [7]–[9]. These results have recently been confirmed by an independent group [10]. In this model, transverse resolution behaves as in a pinhole collimator and axial resolution behaves as in a parallel-beam collimator [7], [11]:

$$R_{\text{tran}} = \left[w^2 \frac{(h+f)^2}{f^2} + \frac{h^2}{f^2} R_i^2 \right]^{\frac{1}{2}} \quad (1)$$

$$R_{\text{axial}} = \left[d^2 \frac{(h+f)^2}{a^2} + R_i^2 \right]^{\frac{1}{2}}, \quad (2)$$

where w is the slit width, h is the distance from a point source to the slit plane, f is the focal length, measured from the slit plane to the detector, a is the height of the slats, R_i is the detector's intrinsic resolution, and d is the gap between slats. Fig. 1 shows these symbols and also defines θ as the angle between the x axis and the vector from the center of the aperture slit to the point source in a y plane containing the point (i.e., $\cot \theta$ measures the ratio of the x and z components of the point source and is independent of y) and t as the thickness of the slats. The distance from the bottom of the slats to the detector surface does not affect the geometric efficiency or resolution relationships since it is already included in f .

The geometric efficiency is given by [7]–[9]:

$$g_{ss} = \frac{wd^2 \sin^3 \theta}{4\pi(d+t)ah}, \quad (3)$$

where the value of $\sin \theta$ is given by the ratio of h to the distance of the point from the aperture slit.

This paper will determine formulas for average geometric efficiency of slit-slat collimation and resolution that are useful for comparison with parallel-beam. These formulas will be a function of the collimator's parameters, which will allow design optimization based on maximizing sensitivity for a given desired resolution. Further, numerical comparisons as a function of cylinder diameter will be made to determine where slit-slat may be better than parallel-beam and fan-beam. The fan-beam comparisons will be limited to a discrete set of focal lengths that are in the range commonly found with clinical systems since it is much more difficult to construct fan-beam collimators with arbitrarily short focal lengths than it is to choose an arbitrary focal length for a slit-slat collimator, although there are ongoing efforts to fabricate short focal-length converging collimators because of their potential advantages in brain imaging [12]. In addition, experimental acquisitions with a prototype collimator and their reconstructions will be shown and compared with expected values of resolution.

II. Methods

A. Design Optimization

For optimizing slit-slat design we start from the premise that we would like to optimize average geometric efficiency over a cylinder of diameter D for given average resolutions $\overline{R_{\text{tran}}}$ and $\overline{R_{\text{axial}}}$ in the transaxial and axial directions, respectively. The length of the cylinder is irrelevant since geometric efficiency and resolution are independent of axial position for slit-slat collimation, as long as the region of interest remains in the axial field of view. Thus, we compute the averages:

$$\begin{aligned}\overline{g} &= \frac{4}{\pi D^2} \int_0^{2\pi} \int_0^{\frac{D}{2}} g \rho d\rho d\varphi \\ \overline{R_{\text{tran}}} &= \int_0^{2\pi} \int_0^{\frac{D}{2}} R_{\text{tran}} W(\rho, \varphi) \rho d\rho d\varphi, \\ \overline{R_{\text{axial}}} &= \int_0^{2\pi} \int_0^{\frac{D}{2}} R_{\text{axial}} W(\rho, \varphi) \rho d\rho d\varphi\end{aligned}\quad (4)$$

where $W(\rho, \varphi)$ is a generalized weighting function for computing the average. It is normalized over the area of a transverse slice (i.e., $\pi D^2/4$):

$$\int_0^{2\pi} \int_0^{\frac{D}{2}} W(\rho, \varphi) \rho d\rho d\varphi = 1. \quad (5)$$

1) Average Geometric Efficiency—The average geometric efficiency of slit-slat collimation can be re-factored:

$$\begin{aligned}\overline{g_{ss}} &= \frac{4}{\pi D^2} \int_0^{2\pi} \int_0^{\frac{D}{2}} \frac{w d^2 \sin^3 \theta}{4\pi(d+t)ah} \rho d\rho d\varphi \\ &= \left(\frac{w}{2\pi^2 D}\right) \left(\frac{d}{a}\right) \left(\frac{d}{d+t}\right) \left(\frac{2}{D}\right) \int_0^{2\pi} \int_0^{\frac{D}{2}} \frac{\sin^3 \theta}{h} \rho d\rho d\varphi.\end{aligned}\quad (6)$$

The first factor is related to transverse resolution, the second to axial resolution, and the third is the packing fraction (i.e., open fraction) for the septa.

We now apply the following substitutions to the double integral in (6):

$$\begin{aligned}\sin \theta &= \frac{h}{\sqrt{h^2 + \rho^2 \cos^2 \varphi}} \\ h &= \frac{D}{2} \csc \frac{\alpha}{2} + \rho \sin \varphi \\ \rho &= \frac{D}{2} u\end{aligned}\quad (7)$$

since the cylinder is tangent to the field of view of the slit with full acceptance angle α (Fig. 2). We introduce:

$$\begin{aligned}I(\alpha) &\equiv \frac{2}{D} \int_0^{2\pi} \int_0^{\frac{D}{2}} \frac{\sin^3 \theta}{h} \rho d\rho d\varphi \\ &= \int_0^{2\pi} \int_0^{\frac{D}{2}} \frac{\left(\frac{2}{D}\right) \left(\frac{D}{2} \csc \frac{\alpha}{2} + \rho \sin \varphi\right)^2 \rho d\rho d\varphi}{\left[\left(\frac{D}{2} \csc \frac{\alpha}{2} + \rho \sin \varphi\right)^2 + \rho^2 \cos^2 \varphi\right]^{\frac{3}{2}}}. \\ &= \int_0^{2\pi} \int_0^1 \frac{\left(\csc \frac{\alpha}{2} + u \sin \varphi\right)^2 u du d\varphi}{\left[\csc^2 \frac{\alpha}{2} + 2u \csc \frac{\alpha}{2} \sin \varphi + u^2\right]^{\frac{3}{2}}}\end{aligned}\quad (8)$$

An exact solution can be found in terms of elliptical integrals [13]. Alternatively, a simple expression can be found for small values of α by keeping only the leading-order $\csc \frac{\alpha}{2}$ terms:

$$I(\alpha) \approx \int_0^{2\pi} \int_0^1 \sin \frac{\alpha}{2} u du d\varphi = \pi \sin \frac{\alpha}{2}. \quad (9)$$

The numerical values of $I(\alpha)$ and its approximation are shown in Fig. 3. Using $I(\alpha)$, the average geometric efficiency can be written as:

$$\overline{g_{ss}} = \left(\frac{w}{2\pi^2 D} \right) \left(\frac{d}{a} \right) \left(\frac{d}{d+t} \right) I(\alpha). \quad (10)$$

The value of t is chosen to be sufficiently large to keep septal penetration reasonably small [14]. However, large values of t reduce geometric efficiency through the packing-fraction factor, $d/(d+t)$. To mitigate the effect of this factor, which is ≤ 1 , we choose to make d as large as possible while maintaining resolution, which in turn requires making the slat height a large. Theoretical limits on a would allow the slats to be tangent to the field of view. However, practical limits on a stem from mechanical constraints of the collimator shielding. For example, it may be possible to design a system with $a > f$, but that would make the slats vulnerable to damage because they would extend beyond the slit. Thus, we constrain $a = f - c$, where c is the loss in slat height due to mechanical constraints in the design.

2) Average Resolutions—A general analytic solution for the values of w and d/a that match the desired average resolutions in the transaxial and axial directions, respectively, to those of parallel-beam is unknown to the authors. However, upper bounds can be placed. In the case of transaxial resolution,

$$\begin{aligned} \overline{R_{\text{tran}}} &= \int_0^{2\pi} \int_0^{\frac{D}{2}} \left[w^2 \frac{(h+f)^2}{f^2} + \frac{h^2}{f^2} R_i^2 \right]^{\frac{1}{2}} W(\rho, \varphi) \rho d\rho d\varphi \\ &\geq \int_0^{2\pi} \int_0^{\frac{D}{2}} w \frac{(h+f)}{f} W(\rho, \varphi) \rho d\rho d\varphi \\ &= w \frac{(\overline{h}+f)}{f}, \end{aligned} \quad (11)$$

which gives

$$w \leq \overline{R_{\text{tran}}} \frac{f}{(f+\overline{h})}, \quad (12)$$

where

$$\overline{h} = \int_0^{2\pi} \int_0^{\frac{D}{2}} h W(\rho, \varphi) \rho d\rho d\varphi. \quad (13)$$

Similarly,

$$\frac{d}{a} \leq \frac{\overline{R_{\text{axial}}}}{(f+h)}. \quad (14)$$

The above values provide starting points (i.e., seeds) for numerically determining the values of w and $\frac{d}{a}$ that match resolution. These values are functions of f . Thus, one needs to consider all values of f to determine the optimal configuration parameters. It is clear from physical arguments that there is a maximum for average geometric efficiency with respect to f since $f = 0$ does not allow transaxial resolution matching and a large value of f causes the acceptance angle α to be small, which increases the radius of rotation, which decreases the geometric efficiency.

In the special case where the weighting function $W(\rho, \varphi)$ is chosen so that the average resolution is the resolution at the center of the cylinder (i.e., $W(\rho, \varphi) = \frac{\delta(\rho)}{2\pi\rho}$), the values of w and $\frac{d}{a}$ are readily calculated from (1) and (2):

$$\begin{aligned} w &= \frac{\left(\overline{R_{\text{tran}}}^2 f^2 - \frac{D^2 R_i^2}{4} \csc^2 \frac{\alpha}{2} \right)^{\frac{1}{2}}}{\frac{D}{2} \csc \frac{\alpha}{2} + f} \\ \frac{d}{a} &= \frac{\left(\overline{R_{\text{axial}}}^2 - R_i^2 \right)^{\frac{1}{2}}}{\frac{D}{2} \csc \frac{\alpha}{2} + f}. \end{aligned} \quad (15)$$

Throughout the remainder of this paper, we use this specific weighting, which is analytically tractable, although other weightings that may be more appropriate for a specific task could be used numerically following the methods outlined above.

To minimize slit penetration, we impose the further constraint between α and the the focal length that:

$$\alpha = \min\left(2\tan^{-1} \frac{L}{2f}, \alpha_{\text{max}}\right), \quad (16)$$

where L is the transverse detector size. All the factors in (10) are a function of f and $\overline{g_{ss}}$ may be maximized with respect to f . The choice of α_{max} depends on how much slit penetration and detector parallax (depth-of-interaction effect) to allow. We have chosen a value of 120 deg. for this study.

B. Best Achievable Resolution

The best achievable (BA) resolution of a system – measured at the center of the object – is achieved in the limit as geometric efficiency goes to zero. To determine the BA resolution in the transaxial direction for slit-slat, we set $w = 0$. Applying this to (1),

$$\begin{aligned} R_{\text{tran}}(\text{BA}) &= \frac{h}{f} R_i = \frac{D R_i}{2f} \csc \frac{\alpha}{2} \\ &= \frac{D R_i}{L} \sqrt{1 + \left(\frac{L}{2f}\right)^2}, \\ &= \frac{D R_i}{L} \end{aligned} \quad (17)$$

where the last line is found by maximizing with respect to f . To determine the BA resolution in the axial direction for slit-slat, we set $\frac{d}{da}=0$:

$$R_{\text{axial}}(\text{BA})=R_i. \quad (18)$$

The BA axial resolution for both slit-slat and parallel-beam collimation is the intrinsic resolution of the detector. For parallel-beam, axial and transaxial resolutions are the same, so the BA transaxial resolution for parallel-beam is also the intrinsic resolution. Fig. 4 shows the BA resolutions, normalized by the intrinsic resolution (e.g., $R_{\text{tran}}(\text{BA})/R_i$), for slit-slat and parallel-beam as a function of D/L .

C. Slit-Slat Performance Versus Parallel-Beam

The value of $\overline{g_{ss}}$ was numerically optimized with respect to f , using (15), for different values of isotropic resolution (4, 5 and 10 mm) at the center of the object using an intrinsic resolution $R_i = 3.5$ mm and $c = 10$ mm. The maximum value of $\overline{g_{pb}}$ was obtained using the methods in [14], which also maximizes sensitivity under the constraints of a desired, fixed resolution at the center and limited septal penetration, with the additional constraint that $t \geq 0.1$ mm for mechanical stability; this same constraint is applied to slit-slat collimation.

D. Multislit-Slat Performance Versus Parallel-Beam and Fan-beam

We consider multislit-slat collimation that has a center slit and two side slits. No overlap of projections from the slits is allowed. This system introduces two new parameters in the optimization: the fraction of the detector dedicated to the center slit (p) and the distance between slits (s) (Fig. 5). We assume that all the apertures are in the same plane. This assumption results in all slits having the same value of w to match resolution at the center of the object since they are all the same perpendicular distance (i.e., measured along the z axis) h to this point. In particular, the slit width is measured along the x axis and, when $w=0$, the slit edges forming the apertures meet in the same z -plane.

The value of average geometric efficiency for a multislit-slat collimator was numerically optimized with respect to f , s , and p for a detector that was 54 cm in the transverse direction. The system resolutions at the center of the object were 4, 5, and 10 mm in both the transverse and axial directions. In addition, a data set with 2 mm transaxial resolution and 8 mm axial resolution is shown; this set has the same geometric-mean resolution as that of the 4 mm isotropic set, but is unreachable by parallel-beam collimation since 2 mm is less than the intrinsic resolution of 3.5 mm. The motivation for choosing the geometric-mean is that it is directly related to sensitivity in the absence of detector-resolution effects (i.e., if the size of an aperture (hole) – parallel-beam, pinhole, or slit – is increased in one dimension, the resolution increases (degrades) proportionally in that dimension and the sensitivity increases proportionally).

A particular optimal configuration for multislit-slat and parallel-beam was chosen for approximately equal geometric efficiency at a matched isotropic resolution of 4 mm. This configuration, which will be described in Section III-B, was then held fixed while the object diameter was varied. The geometric efficiency and resolutions were calculated as a function of object diameter. The motivation for holding the configuration fixed is that the hole parameters of a real parallel-beam (or fan-beam) collimator cannot be changed nor can the slit height or separation of a real multislit-slat be changed without great difficulty.

A comparison with fan-beam is complicated by the choice of focal length, which we define as the distance from the patient-side of the collimator to the focal line of the collimator. We use

three focal lengths, which cover a range similar to that of clinically available fan-beam collimators: 45 cm, 55 cm, and 65 cm. The data will be presented both as a ratio of fan-beam to parallel-beam and in tabular form showing the object diameter at which multislit-slat's efficiency is equal to that of parallel-beam and fan-beam. To calculate the efficiency gain due to fan-beam, two factors were considered. First, the increase in hole size to achieve the same resolution; the fan-beam's hole size is increased because its magnification reduces the effect of detector resolution. Second, there is a gain from the efficiency factor $F \cos^3 \omega / (F - b)$, where F is the focal length, b is the distance of the source from the detector, and ω is the complement of the photon's incidence angle with the detector [15]; this factor was numerically integrated over the object.

E. Phantom Experiments

1) Description of Collimator and Acquisition—A prototype multislit-slat collimator was constructed using a rectangular lead box to provide shielding from environmental photons (Fig. 6). The box was filled with 125 mm-tall lead slats ($a=125$ mm) that were 0.15 mm-thick ($t=0.15$ mm). The slats were held flat using 3 mm-thick Rohacell foam ($d=3.0$ mm; 0.031 g/cm³); at normal incidence photons pass through 3.1 cm of Rohacell foam with an approximate attenuation of 2% at 140 keV (based on the tabulated attenuation of similar materials [16] and on experimental measurements). This attenuation factor was not considered in the optimization since it depends in detail on the amount of Rohacell foam used. The distance from the slit plane to the detector plane, f , was 145 mm. Two different slit widths (w) were used: 1.0 mm and 2.0 mm; the distance between slits (s) currently has two configurations and depends on w , but for this experiment it was held at 47 mm when w was 2.0 mm (i.e., 45 mm + w).

The box was mounted on one head of a triple-camera SPECT system (Triad-XLT, Trionix Research Laboratories, Inc., Twinsburg, OH 44087). Each gamma camera has a rectangular field of view (FOV) of 40 cm transaxially and 22 cm axially. The scintillation crystal has a thickness of 9.5 mm.

Phantom data were acquired using a micro hot-rod phantom (Model ECT/HOT/MMP, Data Spectrum Corp., Hillsborough, NC) with $w = 2.0$ mm and both the single-slit and multi-slit configurations. In addition, micro cold-rod and Deluxe Jaszczak phantoms (Models ECT/DLX/MMP ECT/DLX/P, respectively, Data Spectrum Corp., Hillsborough, NC) was filled with aqueous ^{99m}Tc pertechnetate. All acquisitions used 180 views (2 deg. step) with a view time of 30 s/view for the micro phantoms and 30 s/view for the Deluxe Jaszczak phantom.

The micro hot-rod phantom had 9.9 mCi of activity for the single-slit scan and 7.8 mCi of activity for the multi-slit scan. In both cases, w was 2.0 mm. The radius of rotation (ROR) was 48 mm. The micro cold-rod had 18 mCi of activity for the $w = 1.0$ mm scan and 14 mCi for the $w = 2.0$ mm scan; both were at an ROR of 37 mm. The Deluxe Jaszczak phantom was filled with 26 mCi of activity for the $w = 1.0$ mm scan and 26 mCi for the $w = 2.0$ mm scan; both were at an ROR of 163 mm.

2) Calibration for Mechanical Shift—The mechanical and electronic shifts of the system were determined using a point-source scan with the same setup as for the phantom acquisitions. The mechanical shift of the system, τ_x , is the transaxial distance from the center of the slit to the axis of rotation (AOR). This factor causes a magnification-dependent shift of the projection. The electronic shift, ϵ_x , is the difference between the actual electronic readout of a particular physical position on the detector and the actual position. One potential source of electronic shift is the mis-positioning of the detector; the projection data may be corrected by a constant translation, unlike for mechanical shifts.

The point source was acquired using 120 views. The transaxial centroid (C_x) of each projection was calculated and used in the fit to the equation [17]:

$$C_x = \tau_x + \varepsilon_x + f \frac{\tau_x - x_0 \cos \varphi - y_0 \sin \varphi}{ROR + x_0 \sin \varphi - y_0 \cos \varphi}, \quad (19)$$

where φ is the rotation angle of the source and (x_0, y_0) is the position of the point source. The output of the fit is τ_x , ε_x , and (x_0, y_0) . The mechanical shift was found to be 0.38 mm for the center slit, measured relative to the axis of rotation.

3) Reconstruction—The projection data were reconstructed using an ordered-subset maximum-likelihood estimation-maximization iterative algorithm that modeled the point-spread function and geometric efficiency based on (1) and (3), respectively. Each slice was treated independently; thus, axial resolution was not modeled. For reconstructing the micro hot-rod and cold-rod phantom, there were 110 voxels (0.5 mm edge length) in the transverse directions and 128 voxels in the axial direction, matching the detector pixel size (i.e., 1.78 mm). The micro hot-rod was reconstructed using both single-slit and multi-slit projection data. For reconstructing the Deluxe Jaszczak phantom, there were 175 voxels (1.5 mm edge length) in the transverse directions and 128 voxels in the axial direction. Ten iterations were performed with four subsets. A circular attenuation map ($\mu = 0.15 \text{ cm}^{-1}$) centered on the axis of rotation was used for the Deluxe Jaszczak phantom.

III. Results

A. Slit-Slat Performance Versus Parallel-Beam

The values of $\overline{g_{ss}}$, as calculated in (10), and $\overline{g_{pb}}$, as calculated using the methods in [14], are shown for different values of isotropic resolution (4, 5 and 10 mm) at the center of the object using an intrinsic resolution $R_i = 3.5 \text{ mm}$ and $c = 10 \text{ mm}$ as a function of D in Fig. 7 for transaxial detector sizes of 40 cm and 54 cm. The slit-slat data in Fig. 7(right) begin to differ at large values of D from that of Fig. 7(left). That is, only at larger values of D does the larger detector improve performance.

B. Multislit-Slat Performance Versus Parallel-Beam and Fan-beam

The value of average geometric efficiency for a multislit-slat collimator is shown in Fig. 8 for isotropic resolutions of 4, 5, and 10 mm and for a detector that is 54 cm in the transverse direction. In addition, multislit-slat data for transverse and axial resolutions of 2 mm and 8 mm, respectively, are shown. The geometric mean of this set is the same as that of the 4-mm set, but this configuration is unreachable by parallel-beam collimation. The parallel-beam data for 4, 5, and 10 mm isotropic resolution are also shown; they are the same as in Fig. 7(right).

For comparison with the parallel-beam and multislit-slat results, Fig. 9 shows the efficiency improvement factor obtained at matched resolution for several configurations of fan-beam collimation. Table I shows the value of the object diameter at which multislit-slat's efficiency is equal to that of parallel-beam and fan-beam for different values of matched resolution and fan-beam focal lengths.

Fig. 8 shows that the curves for parallel-beam and multislit-slat with isotropic resolutions of 4 mm are approximately equal at $D=14 \text{ cm}$ with the multislit-slat collimator with transverse and axial resolutions of 2 mm and 8 mm, respectively. The values of the parallel-beam collimator at this point ($d=0.42 \text{ mm}$; $a=22.0 \text{ mm}$; $t=0.10 \text{ mm}$) were kept fixed for the next study. In addition, the multislit-slat configuration parameters for the isotropic ($w=1.71 \text{ mm}$;

$d=1.00$ mm; $t=0.10$ mm; $a=100$ mm; $f=110$ mm; $p=0.64$) and the non-isotropic ($w=0.90$ mm; $d=4.76$ mm; $t=0.10$ mm; $a=190$ mm; $f=200$ mm; $p=1.00$) cases were kept fixed. We then determined the average geometric efficiency and resolution at the center for different values of object diameter; in this calculation, the separation between the slits, s , was re-optimized, but all other parameters were held fixed. The reason for allowing re-optimization is that a slit-slat's slit can be readily adjusted on an object-by-object basis. The results are shown in Fig. 10.

C. Experimental Results

1) Phantom Projections—Sample projections with a single slit and multiple slits are shown in Fig. 11.

2) Reconstructions—Reconstruction for the micro hot-rod phantom, performed on a $110 \times 110 \times 128$ grid of voxels that were 0.5 mm in the transverse direction and 1.78 mm in the axial direction, is shown in Fig. 12. The left image shows single-slit reconstruction and the right image shows multi-slit reconstruction. Both images are for $w=2.0$ mm. Single-slit reconstruction for the micro cold-rod phantom, performed on the same grid as the micro hot-rod, is shown in Fig. 13. The image on the left is for $w = 1.0$ mm; the image on the right is for $w = 2.0$ mm. Both figures are for 3 summed slices. The six sectors of the phantom have rods with diameters of 1.2, 1.6, 2.4, 3.2, 4.0, and 4.8 mm.

Reconstructions for the Deluxe Jaszczak phantom, performed on a $175 \times 175 \times 128$ grid of voxels that were 1.5 mm in the transverse direction and 1.78 mm in the axial direction, are shown in Fig. 14. The image on the left is for $w = 1.0$ mm; the image on the right is for $w = 2.0$ mm. All images are for 10 summed slices to reduce noise. The six sectors of the phantom have rods with diameters of 4.6, 6.4, 7.9, 9.5, 11.1, and 12.7 mm.

IV. Discussion

The geometric efficiency and resolution of slit-slat collimation have previously been validated [7]–[9]. Those formulas have been used to determine the average geometric efficiency as a function of object diameter, as given in (10). This form clearly shows the dependence of average geometric efficiency on collimator parameters. Since the value of average geometric efficiency goes as D^{-1} , one expects this collimator to be good for small values of D .

The best achievable resolution was shown in Fig. 4. This plot and the associated equations show that slit-slat axial resolution and parallel-beam transverse and axial resolutions are limited to the intrinsic resolution of the detector. This is because there is no magnification. However, the transverse resolution for slit-slat can go to zero for small objects, which have large magnifications. This makes one consider the possibility of using slit-slat for imaging scenarios where transverse resolution better than the intrinsic resolution is desired and also when isotropic resolution is not required. Similarly, fan-beam collimation does not yield isotropic resolution.

Numerical comparisons of average geometric efficiencies were made between slit-slat and parallel-beam in Fig. 7. These results show that slit-slat does better than parallel-beam when the object diameter is smaller than a critical value depending on $\overline{R_{\text{tran}}}$. Slit-slat also does better when the desired resolution is better, shifting the cross-over point towards larger-diameter objects. A larger detector (54 cm vs. 40 cm) also favors slit-slat over parallel-beam since higher magnifications are achievable and the collimator may be brought near the object, which improves geometric efficiency (i.e., α increases, which results in an increasing value for $I(\alpha)$ (See (10) and Fig. 3)). However, in this study, the acceptance angle α was limited to 120 deg., which caused the larger detector to be advantageous only at large values of object diameter

when a larger focal length was needed. Moreover, optimizations typically led to values of α that were equal to the maximum allowed (See (16)). This is physically sensible in the absence of penetration since it allows for a small value for the radius of rotation, increasing both sensitivity and resolution.

Fig. 9 shows that fan-beam collimation substantially improves the sensitivity for matched resolution, especially when the matched resolution is smaller (i.e., better). This study did not allow for optimizing the focal length, but several representative values were chosen. Naturally, the smaller the focal length, the larger the improvement in sensitivity. However, this reduces the size of the largest object that can be imaged. Table I shows that the crossover points between multislit-slat and fan-beam are in the range of 8–9 cm in diameter, depending on the desired resolution and focal length.

In practical designs, the slit height, a , is less than – but close to – the slit-slat's focal length f . Consequently, (10) shows that the average geometric efficiency decreases with increasing focal length because d/a decreases with increasing f , as shown in (15). On the other hand, achievable transverse resolution improves with increasing focal length since magnification increases. However, there can be diminishing returns in transverse resolution beyond the magnification needed to overcome the intrinsic resolution. Hence a better use of the detector may be to project multiple copies, as in the case of multislit-slat.

The performance of multislit-slat (MSS) was compared with parallel-beam in Figs. 8 and 10. MSS performs at least as well as single-slit slit (SSS) since the configurations explored varied from using the entire detector for the central slit to using it for the two side slits. MSS improves the geometric efficiency for a fixed resolution compared to that of SSS, extending the crossover points with respect to parallel-beam to larger diameter objects.

An advantage of slit-slat and multislit-slat over parallel-beam and fan-beam collimation is its adjustability. In Figs. 8 and 10, it was assumed that the collimators could be adjusted to give the optimal choice for a given diameter. Although it is important to understand which collimator would be better for a given object diameter and desired average resolution, it is also important to understand how that collimator performs for other object sizes. Fig. 10 shows how geometric efficiency and resolution perform for multislit-slat and parallel-beam as a function of object diameter when the configurations were chosen optimally at an object diameter of 14 cm, where they nearly matched for a 54 cm detector. The geometric efficiency of parallel-beam is flat, as expected, whereas MSS improves as the diameter is reduced. The resolution plot shows that the parallel-beam resolutions and the axial resolution for the isotropic slit-slat have relatively flat slopes; the transverse resolution and the axial resolution for the non-isotropic case have larger slopes. Interestingly, the average transverse resolution for the non-isotropic case remains under 3 mm even for the maximum diameter shown, 20 cm.

One important factor in the comparisons made herein is the choice of weighting, $W(\rho, \varphi)$, to match resolution. Equation (4) gives a generic form for the average resolutions and upper bounds for matching w and $\underline{a}$ are given in (12) and (14), respectively. Much of the rest of the paper considered the simplified case of matching resolution at the center of the object. This may or may not be optimal. For example, one can speculate that using geometric efficiency or the square-root of geometric efficiency as the weighting to calculate average resolution may be more appropriate since the expected reconstructed resolution would improve with more counts. Using these weightings would favor slit-slat over parallel-beam, but no studies of the best choice of weighting have been performed.

This study for optimizing sensitivity considers only the geometric resolution. The rationale is that the difference in penetration is small. When accounting for penetration with slit-slat

collimation, several factors contribute, making it cumbersome to optimize. For example, the effective slit width with penetration has previously been determined to be [9]:

$$w_{se} = w + \frac{1}{\mu} \left(1 - \cot^2 \frac{\alpha}{2} \cot^2 \theta \right) \sin \theta \tan \frac{\alpha}{2}, \quad (20)$$

where μ is the linear attenuation coefficient. Since this penetration depends on θ , the simplifying integral $I(\alpha)$ would need to be re-calculated for every combination. For comparison, at matched resolutions of 4 mm and an object diameter of 10 cm – where average geometric efficiency is about equal for parallel-beam and slit-slat, slit-slat penetration is 16% and parallel-beam is 10% of their average geometric efficiencies, respectively, when considering a 140 keV ^{99m}Tc source, a tungsten slit ($\mu = 36.4 \text{ cm}^{-1}$) and lead slats ($\mu = 24.9 \text{ cm}^{-1}$) [16].

Accurate transaxial resolution and geometric efficiency models were incorporated into a 2D iterative reconstruction through the use of (1) and (3), although axial-resolution modeling was not incorporated since slices were independently reconstructed. The reconstructions in Figs. 12–14 show resolution consistent with expectations from (1), as calculated in Table II. Consistent with the sensitivity results and activity concentrations, there is much less noise in the reconstructions of the micro phantoms than in the reconstructions of the Deluxe Jaszczak phantom.

V. Conclusion

Slit-slat collimation provides a viable choice for tomographic imaging. Herein, the transaxial resolution formula has been found to well predict the transaxial resolution of reconstructions. This collimation is likely to be a better choice than parallel-beam for small to medium objects with a long axial field of view that makes them less appropriate for pinhole imaging, which yields incomplete projection data with only a circular orbit. The advantage of slit-slat over parallel-beam is increased as the desired resolution improves, particularly in the case of non-isotropic resolution, where higher resolution in the transaxial direction is sought. The advantage of multiple slits further enhances the geometric efficiency gain. Lastly, slit-slat can be used to obtain values of resolution that are unreachable by parallel-beam and its adjustability in the transverse direction offers flexibility unavailable in parallel-beam imaging. Slit-slat and multislit-slat (MSS) have the same qualitative advantages over fan-beam, but the quantitative advantage is reduced so that only objects with diameter less than about 8 cm would be imaged better with MSS than a specially designed fan-beam collimator. In summary, slit-slat and multislit-slat offer improved performance compared with parallel-beam and fan-beam collimation for small to medium-sized objects.

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Fig. 1.

Slit-slat geometry. The slit width is w ; it is located a distance f above the detector. The slats have thickness t , height a , and are separated by distance d . The point source is located a distance h above the slit plane and makes an angle θ with the x -axis.

Fig. 2. Geometry of integration and substitution. The disk has diameter D ; it is parameterized by polar coordinates ρ and ϕ . The value of h is $D/(2\sin\frac{\alpha}{2})$.

Fig. 3. $I(\alpha)$ as given in (8) vs. α . For reference, the approximation found in (9) is also shown (dashed).

Fig. 4.

Best achievable transaxial and axial resolutions for slit-slat (SS) and parallel-beam (PB) as a function of the ratio of object size to detector size. The resolutions are normalized by the intrinsic resolution so that a value of unity corresponds to a resolution equal to the intrinsic resolution. Please note that the PB transaxial, PB axial, and SS axial resolutions are the same.

Fig. 5.

Multislit-slat collimation. There is a center slit and two side slits, which are a distance s from the center slit; all slits are in the same plane and have the same aperture, w . The central slit projects onto a fraction p of the detector, the transverse length of which is L . The remainder of the detector is used by the side slits. The center slit does not truncate the object, but the side slits do. The shaded regions in the object indicate the field of view of the side slits.

Fig. 6.
Photograph of the prototype collimator with three slits. The slit width is variable.

Fig. 7. Geometric efficiency of slit-slat (SS) and parallel-beam (PB) collimators for isotropic resolutions of 4, 5, and 10 mm at the center of the object, as a function of the object's diameter. The optimal parameters for each collimator are used at each value of the diameter. The transaxial fields of view of the detector are 40 cm (left) and 54 cm (right). Small differences are seen for the larger detector at large values of object diameter.

Fig. 8.

Geometric efficiency of multislit-slat (MSS) and parallel-beam (PB) collimators for average isotropic resolutions of 4, 5, and 10 mm, as a function of the object's diameter. In addition, MSS is shown with transaxial resolution of 2 mm and axial resolution of 8 mm; the geometric mean of these is 4 mm for comparison with the curves of MSS and PB with isotropic resolution of 4 mm; transaxial resolution of 2 mm is unreachable by PB because it is greater than the intrinsic resolution. The optimal parameters for each collimator are used at each value of the diameter. The transaxial field of view of the detector is 54 cm.

Fig. 9.

Relative efficiency of fan-beam collimation in comparison to parallel-beam collimation for three different focal lengths: 45 cm, 55 cm, and 65 cm, as measured from the patient side of the collimator. Resolutions were matched in the transverse and axial directions at 4 mm, 5 mm, and 10 mm.

(a)

(b)

Fig. 10.

Average geometric efficiency (a) and resolutions at the center (b) of multislit-slat (MSS) and parallel-beam (PB) collimators for fixed collimator parameters, except for possible adjustment to slit separation in the case of MSS. The MSS isotropic data are for resolutions at the center of 4 mm; the non-isotropic set is for 2 mm and 8 mm transverse and axial resolutions, respectively. The transaxial field of view of the detector is 54 cm.

Fig. 11.
A single projection of a micro hot-rod phantom acquired with a single slit (top) and multiple slits (bottom).

(a)

(b)

Fig. 12.

Reconstructions of the micro hot-rod projection data sets. The image on the left is for single-slit acquisition; the image on the right is for multi-slit acquisition. Both use $w = 2.0$ mm and sum 3 slices. The six sectors of the phantom have rods with diameters of 1.2, 1.6, 2.4, 3.2, 4.0, and 4.8 mm. The RORs were 48 mm.

Fig. 13.

Reconstructions of the micro cold-rod projection data using a single slit. The image on the left is for $w = 1.0$ mm; the image on the right is for $w = 2.0$ mm. Both images sum 3 slices. The six sectors of the phantom have rods with diameters of 1.2, 1.6, 2.4, 3.2, 4.0, and 4.8 mm. The RORs were 37 mm.

(a)

(b)

Fig. 14.

Reconstructions of the Deluxe-Jaszczak projection data with attenuation correction, acquired using a single slit. (a): $w = 1.0$ mm. (b) $w = 2.0$ mm. Both images sum 10 slices. The six sectors of the phantom have rods with diameters of 4.8, 6.4, 7.9, 9.5, 11.1, and 12.7 mm. The RORs were 163 mm.

TABLE I

Approximate efficiency cross-over points for multislit-slat (MSS) with parallel-beam (PB) and fan-beam (FB) collimation for a detector field of view of 54 cm. The cross-over point is the object diameter at which the efficiencies are approximately equal. Below that point, MSS is more efficient. Three fan-beam focal lengths are considered: 45 cm, 55 cm, and 65 cm.

Resolution (mm)	PB (cm)	FB (cm)		
		$f=45$ cm	$f=55$ cm	$f=65$ cm
4	14	8	9	9
5	11	8	8	9
10	9	8	8	8

TABLE II

Expected transaxial resolutions at the center for the micro (Fig. 13) and Deluxe Jaszczak phantoms (Fig. 14).

Phantom	w	ROR	$\overline{K}_{\text{tran}}$
Micro Hot	2.0 mm	48 mm	2.9 mm
Micro Cold	1.0 mm	37 mm	1.5 mm
Micro Cold	2.0 mm	37 mm	2.7 mm
Deluxe	1.0 mm	163 mm	4.5 mm
Deluxe	2.0 mm	163 mm	5.8 mm