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Finding Optimized Conditions of Slit-Slat and Multislit-Slat Collimation for Breast Imaging

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Abstract

In order to develop a breast-imaging system for Single Photon Emission Computed Tomography (SPECT) using slit-slat and multislit-slat collimators, we searched for optimized geometric parameters of the collimators. For this study, we employed two independent metrics to validate each result: 1) Signal to Noise Ratio (SNR) based on the Cramer-Rao lower Bound (CRB) and 2) contrast at the same noise level from an ensemble. We calculated SNR values using forward-projection data of an anthropomorphic digital phantom containing two lesions in the breast (one at the chest wall and the other at the center) with a simulated slit-slat collimator as a function of the collimator's geometric parameters. We also calculated contrast values from reconstructed images with noise.

Based on the results from the slit-slat case, we investigated angular range, SNR, and contrast for the multislit-slat. We saw similar trends of the two metrics. One interesting property of the multislit-slat is that the imaging performance depends on the orientation of the field of view (FOV) of the side slits. When we compared the metric values for the slit-slat and multislit-slat, improvement was seen only when the lesion was in the FOV of the side slits. Therefore, tuning the parameters of the multislit-slat to optimally detect lesions at the chest wall might be a sensible option since the slit-slat already provides good image quality for center and superficial lesions.

Index Terms

sensitivity; slit-slat; single photon emission computed tomography (SPECT)

I. Introduction

Slit-slat collimation has existed since SPRINT was constructed in the early 1980's [1].[3]. More recently, this collimator has been evaluated for small-animal imaging [4], [5], human cardiac imaging [6] and brain imaging [7]. It has been shown that this collimator can be well characterized in terms of resolution, sensitivity, and FOV as a combination of a pinhole collimator in the transverse direction and a parallel-beam collimator in the axial direction [8].[12]. Because of these properties the average sensitivity over a cylinder of diameter D is proportional to D^{-1} , which suggests that slit-slat collimation may provide better imaging performance for smaller objects compared to parallel or fan beam collimation [13].

Slit-slat can achieve a small radius of rotation (ROR) due to its tapered profile and complete or nearly complete sampling over the breast with a partial circular orbit because it is subject to 2D sampling unlike pinhole imaging which requires 3D orbits. Further, the tapered design of the housing helps the gamma camera orbit stay close to the breast with a wide angular range. Such features, which provide improved sensitivity and/or resolution compared to fan-beam and parallel-beam collimation, encourage the use of slit-slat collimation for breast imaging.

In this study, the orbit of the slit-slat collimator is approximately from the sternum to the axilla (i.e., lateral view) (Fig. 1). When the collimator approaches the breast by reducing the ROR, the sensitivity and resolution are improved, but the FOV and angular range of the detector are reduced (i.e., reduced sampling). Since breast imaging requires only a small FOV relative to the transaxial detector size (40 cm or greater) of a conventional NaI(Tl) gamma camera, some portion of the detector is not used. To take advantage of the rest of the detector, we added two side slits; three copies of the image are made to improve the geometric efficiency and contrast recovery.

The image quality of tomographic images depends on factors such as the sensitivity, sampling, and system resolution, which are determined by the geometric configuration of the system. Thus, our aim in this study is to evaluate the image quality of the tomographic data acquired from slit-slat and multislit-slat collimators as a function of the collimator parameters.

II. Methods

A. Geometry

1) Slit-Slat Geometry and Characteristics—Figure 2 shows a slit-slat collimator with a slit at a distance f from and parallel to the detector plane. The normals of the slats are parallel to the slit direction. A point source is shown at P . Table I describes parameters that define the geometry of slit-slat collimation. In addition to the parameters, the distance from the point source P to the slit plane is h , and the ratio of h to the distance of the point P from slit i is $\sin\theta_i$.

A multislit-slat collimator is similar to a slit-slat collimator, but has additional slits. In our case all the slits are in the same plane, which is a distance f from the detector plane. Further, one slit is centered on the axis of rotation (AOR) and the two side slits are each a distance s away. Another additional parameter of the multislit-slat collimator is the fraction of the detector area dedicated to the center slit (p). Figure 3 demonstrates the above description.

We constrain p and s with two restrictions: the center slit does not truncate the object and the projected images from the slits do not overlap (i.e., no multiplexing). Similarly to the case of the slit-slat collimator, w , d , a , and t are determined when f and ROR are known while the desired system resolution is specified. The parameters p and s must be selected between their maximum and minimum values. We can vary p from 0% to 100%. It is determined by the acceptance angle (α). The minimum of s must be larger than w because it is a distance from the center of the side slit to that of the center slit and maximum is determined by the transverse FOV of the side slits: the maximum value of s is the first point at which the breast does not project through the side slits onto the detector; the maximum value of s depends on other collimator parameters.

We assume that the detector has transverse length L and the detector's intrinsic resolution is R_i . The transverse and axial resolution of slit-slat collimator [8].[10] are:

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

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

The geometric efficiency through slit i is [8].[10]:

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

Previously, our group performed a study that determined the values of slit-slat parameters for a given system resolution by employing physical constraints [13]. We found that there are only two free parameters: f and ROR. Based on the relationship between parameters and constraints, the optimization of slit-slat collimator and multislit-slat collimation are the problems of searching for the maximum value of a function in the 2D and 4D parameter spaces, respectively: we altered f and ROR between the upper and lower bounds for the slit-slat collimator (2 free parameters) and altered f , ROR, p , and s for the multislit-slat collimator (4 free parameters).

2) Breast-Imaging Geometry—For this study, we used an anthropomorphic thorax phantom [14] with 128^3 voxels (0.356 cm edge length) to simulate the lesion activity and background. The digital torso phantom, which had one breast, represented a prone patient on a special table. The orbit of the gamma camera rotated around the pendulous breast which was the region of interest (ROI).

Since our focus was on the dependence of the reconstructed image quality on the collimator parameters in the breast area, we assigned the same activity concentration of Tc-99m to all organs and tissues for background. We used the same total scan time and the same number of projection views for each instance of the simulated collimator.

Two lesions of identical size (1 cm diameter) and activity concentration were placed near the chest-wall and the AOR, which is centered in the breast. The concentration ratio was

$$\text{lesion:background}=6:1. \quad (4)$$

3) Angular Range versus Geometric Parameters—The ROR cannot be shorter than 8 cm when the AOR is focused on the center of breast in order to clear the breast. A large ROR degrades the geometric efficiency, but increases the angular range of the camera head. When the ROR value is picked, f must be longer than a certain minimum to match the desired resolution [13]:

$$f \geq \frac{\text{ROR}}{\overline{R_{\text{tran}}}} R_i. \quad (5)$$

where $\overline{R_{\text{tran}}}$ is the matched transverse resolution at the center of the breast (i.e., the AOR), which is very similar to the average transverse resolution over the breast.

There is also a physical limit to $f + \text{ROR}$ given by the camera head's radial range. Based on the above constraints, we bounded f and ROR between 8 cm and 20 cm and varied them by 1 cm increments. In addition to f and ROR, the given resolution and constraints determine the rest of parameters of the slit-slat collimator. In this study, the intrinsic resolution of the detector is 3.5 mm and we assigned the system resolution to be 5 mm.

For each collimator configuration, we modeled the geometry in the context of the digital phantom and rotated the model until it almost hit the body. We required the projection of the breast not to be truncated. Table II shows examples of angular ranges. Fig. 4 shows the relation between the angular range with respect to both f and ROR.

Multislit-slat collimation requires optimization with respect to two additional parameters: p and s . We changed values of p in the range of 20% – 90%, in 10% increments because the distance of $f + \text{ROR}$ is beyond the physical limits to avoid truncation when p is less than 20% and when $p = 100\%$ the multislit-slat becomes a single slit. We varied s by 1 cm between 2 cm and 12 cm. The value of p does not affect the angular range but the value of s does because the transaxial width of the collimator top depends on it. The angular ranges for the multislit-slat collimator were determined the same way as for the slit-slat collimator. As shown in Table III, the smallest f and ROR values are 8 cm each. Since the transverse view of the multislit-slat collimator is wider than that of the slit-slat collimator, angular range is limited and more space is needed between the collimator and body to clear the breast.

B. Metrics for Optimization

We investigated two quantities as figures of merit of image quality: 1) signal to background ratio using Cramer Rao Bound (Fisher information matrix) and 2) contrast at the same noise based on ensembles.

1) Signal to Noise Ratio—We computed the signal to noise ratio SNR utilizing the Cramer Rao lower Bound (CRB). The SNR is calculated from the forward-projection data, which is modeled as the following formulation of Park et al. [15]:

$$I(\vec{x}) = A_1 l(\vec{x}) + A_2 b(\vec{x}), \quad (6)$$

where $l(\vec{x})$ is the projection of the lesion with unit concentration, and $b(\vec{x})$ is the projection of the background with unit concentration. A_1 is the activity concentration of the lesion and A_2 is the activity concentration of the background. Finally the SNR is formulated by [15]

$$SNR = \frac{A_1}{\sqrt{[J^{-1}]_{11}}}, \quad (7)$$

where $[J^{-1}]_{11}$ is the (1,1) element of the inverse of the Fisher information matrix [15]. When we calculated SNR of the chest-wall lesion, the center lesion was not present in the breast area, and vice versa: the two lesions were processed independently and the background was pure background.

2) Contrast at The Same Noise—To validate the SNR based on CRB, we produced forward-projection data of the digital torso phantom using simulated slit-slat and multislit-slat collimators. Since our premise was noise measured from multiple scans under the identical circumstances is modeled by a Poisson distribution, we prepared 200 ensembles for each forward projection selected by Poisson sampling.

The reconstruction was 2D (i.e., slice by slice) using a maximum likelihood expectation maximization (MLEM) with 10 iterations. Therefore, we reconstructed only two slices in the data: one with lesions and one with background only. To obtain the lesion (l), we measured the mean activity concentration in each reconstruction in the region of a lesion from the signal slice. Similarly, the background (b) was taken by measuring the mean value of the same region from the background slice. The contrast is defined as: $c = (l - b)/b$. Noise is defined as the standard deviation of the contrast over ensembles.

The contrast and noise values were calculated for every iteration. Thus, the reconstructed images can be summarized by contrast vs. noise curves. When a certain value of noise is picked, one contrast value indicates the image quality of a slit-slat or multislit-slat collimator built by a set of geometric parameters.

III. Results

A. Optimized condition of slit-slat collimator

We varied ROR and f from 8 cm to 20 cm in 1 cm steps giving 169 different f – ROR combinations. When ROR is small (e.g. 8 cm), f has an upper bound otherwise the projected image is truncated because of transaxial magnification. There is also a lower bound of f for a given ROR otherwise the sought resolution cannot be matched. Only 128 out of the 169 f – ROR combinations meet these conditions.

We produced 128 forward projections and calculated SNR based on CRB. Figure 5 shows SNR vs. f for several values of ROR. Slit-slat collimation with ROR = 8 cm, f = 14 cm, average sensitivity = 3.99×10^{-5} , w = 0.29 cm, d = 0.21 cm, a = 13 cm, and t = 0.01 cm yields the maximum SNR.

In order to present the results in a concise manner and compare to the first metric, we picked the contrast value at the same noise level (0.1) as a second metric. The noise was an absolute value of standard deviation of the contrast. Since authors assumed 200 instances were large enough, RMS denotes the noise of the contrast in the figures. Similarly to the SNR cases, we calculated contrast at the same noise for the maximum angular range (Fig. 6(a) and 6(b)).

We investigated the interrelation between parameters. Figure 7 shows the SNR vs. the angular range of the detector and the contrast at the same noise vs. the angular range of the detector, respectively. The optimized condition of the slit-slat collimator was found at ROR = 8 cm and f = 14 cm with average sensitivity = 3.99×10^{-5} , w = 0.29 cm, d = 0.21 cm, a = 13 cm, and t = 0.01 cm.

B. Optimized condition of multislit-slat collimator

For multislit-slat, we investigated the relationship between parameters for the SNR based on CRB and the contrast at the same noise. Figure 8 shows the metric value vs. pair of given f and ROR values when the remaining parameters are fixed. Figure 9 shows what s maximizes the metric value when the remaining parameters are fixed. Since we learned the general patterns of the SNR and the contrast at the same noise are very similar from the slit-slat case, only the contrast at the same noise is shown here.

The metric values for the chest-wall lesion is maximized at f = 9 cm, ROR = 8 cm, p = 60%, s = 9 cm, average sensitivity = 5.35×10^{-5} , w = 0.2 cm, d = 0.17 cm, a = 8 cm, and t = 0.01 cm and those for the center lesion is maximized at f = 9 cm, ROR = 8 cm, p = 60%, s = 7 cm, average sensitivity = 5.4×10^{-5} , w = 0.2 cm, d = 0.17 cm, a = 8 cm, and t = 0.01 cm. We compared the contrast values of the optimized multislit-slat and slit-slat collimators. Multislit-slat provides 39% and 21% improvement for the chest-wall and center lesions respectively compared to slit-slat.

We also investigated how the orientations of the side slits, which is determined by s , affect the metric values and the angular range around the optimized condition of the multislit-slat collimator (Fig. 10).

C. Reconstructions

In order to evaluate the optimized conditions of the slit-slat and multislit-slat collimators qualitatively, we analyzed reconstructed images of the chest-wall and center lesions. Figure 11 shows the comparison of the reconstructed images obtained from the optimized slit-slat collimator and those obtained from a parallel beam collimator with 360° orbit. Figure 12 shows the reconstructed images of the chest-wall and center lesions obtained from the optimized multislit-slat collimator and those obtained from the optimized slit-slat collimator.

IV. Discussion

In this study, we pursued two main objectives: 1) in order to take advantage of the benefits of the Slit-Slat collimator (complete data acquisition of each slice with high sensitivity and resolution for a mid-size object) for a practical application, we searched for the optimized geometric parameters for breast imaging; and 2) in order to fully utilize the detector, we added two extra slits and investigated the parameters for Multislit-slat collimation.

A. Optimization of slit-slat collimator

When ROR is smaller than 8 cm, the angular range becomes small, so that the collimator does not hit the body. In addition, the angular range decreases with increasing f when ROR is 8 cm (Fig. 4(a)). We observed that the transverse size of the projection of the breast becomes larger as the detector comes closer to the axilla region. Therefore, when ROR is 8 cm the limitation is truncation. When ROR is greater than 11 cm, the projection is not truncated. Instead, the angular range is limited by the clearance of the body. The angular range can be expanded until the base of the collimator hits the body. Thus, larger f allows wider angular range. When ROR is greater than 17 cm, the upper base of the collimator hits the body, so f does not affect the angular range.

According to (3), the average sensitivity of the breast is proportional to the inverse of the distance between the source of the photon and the center of the slit (h^{-1}), which means smaller values of h increase the sensitivity. In this study, we placed the AOR on the center of the breast: the average h^{-1} is approximately equal to ROR^{-1} , so smaller ROR values (nearer distances between the center of the breast and the center of the slit aperture) produce higher average sensitivity over the breast.

In order to quantify the image quality derived from the collimators built with different geometric parameters, we used two independent metrics: SNR based on CRB and the contrast at the same noise. Since these are two different methods, complete similarities of the distributions of the parameters are not expected. However, two metrics are maximized at the same values of the parameters for the slit-slat and multislit-slat collimators and suggest the same idea: the geometric configurations that provide high average sensitivity over the breast produce high metric values.

We investigated the relationship between the two metric values and the angular range (Fig. 7). The metric values were calculated for the chest-wall and center lesions separately. On the other hand, the average sensitivity over the breast is one value which is like the sensitivity of a point located on the center of the breast. Therefore, the patterns of the SNR and contrast at the same noise for the center lesion are closer to the patterns of the sensitivity compared to those for the chest-wall lesion which is located approximately 4 cm higher from the center. The SNR values were calculated from noiseless forward-projection data while the contrast values at the same noise were calculated from ensemble. So, the patterns of the SNR are smoother than those of the contrast.

Based on our investigation, we found the optimized condition of slit-slat collimator at $f=14$ cm and $\text{ROR}=8$ cm. The behavior of the SNR based on CRB for all possible parameters agrees with that of the contrast at the same noise using ensembles. In addition, the sensitivity can be used as a metric to narrow down the range for optimal parameters of slit-slat collimator.

B. Optimization of multislit-slat collimator

Our main goal of developing multislit-slat is to increase sensitivity by using the side slits to produce additional copies of the projection in the portion of the detector that is not utilized

by the center slit. In this structure, the FOV of the side slit is small and the distance between the center slit and side slit s determines the orientation of the FOV. Therefore, supplementary information of the distribution of the radiotracer due to the side slit can be obtained only for the particular area where the FOV of the side slit is centered. Because of this, the value of s that maximizes the metrics depends on the location of the lesion while f , ROR, and p are consistent. Thus, the multislit-slat may be useful to focus on the chest-wall, which is hard to image.

Figure 10 shows the impact of s on the angular range. Since the value of s determines the width of the upper base of the multislit-slat collimator, larger s reduces the angular range of the detector to clear the breast. In the figures, curves fall steeply as s decreases. When s is larger than a certain value, the top part of the collimator hits the body. On the other hand, when s gets smaller than the value the bottom part hits the body. Therefore, the angular range does not increase since the width of the bottom of the collimator is fixed. When s is small, the FOV of the side slits does not contain the lesions. Thus the metric values decrease. Because of the side slits, the angular range of the multislit-slat collimator is smaller than that of the slit-slat collimator (Table II and III). However, additional photons received from the side slits increase the sensitivity and compensate for the loss of the sampling due to the reduced angular range compared to the slit-slat collimator.

Our approach was operating the gamma camera with the slit-slat collimator near the breast to focus the FOV on the breast area to improve lesion detection. Even if the configurations engender small angular ranges and cause artifacts outside the region of interest, which is one limitation of this method, the contrast of the lesions in the breast is significantly higher (Fig. 15(a)) compared to the reconstruction of the entire body scan, which requires a large ROR near the breast (Fig. 14(b)). We compared the performance of the optimized slit-slat and multislit-slat collimators. With respect to the chest-wall lesion, multislit-slat collimation provides a clearer shape of the lesion and smoother background area compared to the recovery of the center lesion. Since the slit-slat collimator obtains sufficient sensitivity and sampling for the center lesion, extra information from the side slits of the multislit-slat collimator seems redundant.

C. Limitations and Future Work

A limitation of this study is that the phantom simulated a uniform background instead of a detailed background distribution that may be attributed to a specific radiopharmaceutical (e.g., sestamibi). Although a specific distribution may affect the optimal design, the impact is likely to be small due to the r^{-1} decrease in sensitivity for slit-slat collimation.

We assumed the reconstruction converges quickly and used 10 iterations of MLEM. More studies might be necessary to determine appropriate iteration numbers. However, in order to validate our ensemble study with 10 iterations, we performed the independent test using SNR based on CRB and the two results showed very close values of the parameters for the optimized condition. In addition, when we compared the performance of the optimized slit-slat and multislit-slat qualitatively, we used 50 iterations of MLEM and our observation agreed with the results. Therefore, we anticipate future works with larger number of iteration will provide the same answer.

We chose the breast area as the ROI and did not consider lesions in the axilla area (lymph node), which is another limitation of this study. We plan to contain the axillary lesions in future work. Before the detailed investigation, we took a quick test for a lesion in the axilla using the SNR based on CRB (Fig. 13). Since we set the AOR on the center of the breast and the lesion is far from the center, the lesion is not always seen by the FOV of the slit-slat and multislit-slat collimators. Therefore, SNR value of the axillary lesion is not as high as

the values of the center and chest-wall lesions. In order to detect axillary lesions efficiently, we might need to think about different camera orbit.

According to [16], optimal system resolution for a 1 cm lesion is approximately 1 cm. However, we assigned 5 mm for a desired resolution. As pointed above, we selected the slit aperture and slit gap sizes to match the desired resolution for given f and ROR. Our result showed that the optimized geometry of the collimator was found when ROR is small and the lesions are exposed by the FOV of the collimator as much as possible. Thus, we expect different resolutions do not affect the optimized geometric parameters. We will investigate various system resolutions in the future works though.

V. Conclusion

In this study, we searched the optimized configurations of the slit-slat and multislit-slat collimators for breast imaging in 2D and 4D parameter spaces, respectively. We used two metrics (SNR based on CRB and contrast at the same noise) to find the optimized geometry. We found a parameter set that maximizes one metric also maximizes the other metric value. We looked into the dependence of the metrics on the dependent parameters such as the sensitivity and the angular range of the camera orbit. We determined that the sensitivity plays a more significant roll in improving the image quality compared to the angular range. The optimized parameter set of the slit-slat collimator for breast imaging is found at $f = 14$ cm, ROR = 8 cm. The optimized condition of the multislit-slat collimator for the chest-wall lesion is found at $f = 9$ cm, ROR = 8 cm, $p = 60\%$, and $s = 9$ cm and that for the center lesion is found with the same values except $s = 7$ cm. The multislit-slat collimator improves the contrast recovery about 39% and 21% for the chest-wall and center lesions, respectively, over the slit-slat collimator.

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Fig. 1. Figure demonstrates an anthropomorphic digital phantom containing two lesions in the breast, the detector orbit from the sternum to the axilla and the angular range (i.e., lateral view).

Fig. 2.

Conceptual design of slit-slat collimator. Photons from the point source P must pass through the slit and between the slats to be detected. The geometric parameters are described in Table I. The slit direction (y) is parallel to the axis of rotation.

Fig. 3.

Schematic diagram of the multislit-slat collimation. The center slit does not truncate the object, and no multiplexing is allowed. Thus, an acceptance angle, α , of the center slit is determined by f and pL . The orientation and acceptance angle of the side slits are determined by s .

Fig. 4.

The dependence of angular range of the camera head on f (left) for several ROR values and on ROR (right) for several f values. Graphs demonstrate the relationship between data points in Table II

(a) Chest-wall

(b) Central

Fig. 5. SNR vs. f for several ROR values. The chest-wall lesion is shown on the left; the central lesion, on the right.

(a) Chest-wall

(b) Central

Fig. 6. Contrast at the same noise vs. f for several ROR values obtained with the slit-slat collimator. The chest-wall lesion is shown on the left; the central lesion, on the right.

(a) Samples of f : chest-wall (b) Samples of f : central (c) Samples of f : chest-wall (d) Samples of f : central**Fig. 7.**

SNR vs. angular range of the detector with the slit-slat collimator. Top: ROR values are varied for given f values. Bottom: f values are varied for given ROR values. The chest-wall lesion is shown on the left; the central lesion on the right.

(a) Sample values of f and ROR: chest-wall (b) Sample values of f and ROR: central

Fig. 8.

The relation between contrast at the same noise of the multislit-slat collimator and pairs of f and ROR when remaining parameters are fixed.

(a) Sample values of s : chest-wall(b) Sample values of s : central**Fig. 9.**

The relation between contrast at the same noise of the multislit-slat collimator and s when remaining parameters are fixed.

(a) SNR vs. angular range; chest-wall

(b) SNR vs. angular range; central

(c) Contrast at the same noise vs. angular range; chest-wall

(d) Contrast at the same noise vs. angular range; central

Fig. 10.

The dependence of contrast at the same noise of the multislit-slat collimator on angular range for sample values of small f and ROR. When f and ROR are determined, p is minimized to increase incoming photons from the side slits. The contrast at the same noise is a function of s which corresponds to a particular angular range value. The angular range decreases as s increases from 2 cm to 12 cm.

(a) Reconstructed image: optimized slit-slat collimator.

(b) Reconstructed image: parallel beam collimator with 360° orbit.

Fig. 11.

To demonstrate the influence of the optimized parameters, we compared the reconstructed images produced from the optimized slit-slat with partial orbit and those from the parallel beam collimator with 360° orbit.

(a) Optimized slit-slat.

(b) Optimized multislit-slat.

Fig. 12.

Comparison of the imaging performance of the optimized multislit-slat collimator with $s = 9$ cm and that of the slit-slat collimator.

(a) Axillary lesion.

(b) The dependence of SNR on angular range.

Fig. 13.

The phantom with an axillary lesion and the behavior of SNR using the optimized geometric parameters of multislit-slat

(a) The dependencies of w and d on the resolution. (b) SNR vs. f when the system resolution is 10 mm.

Fig. 14.

Left plot shows how the slit aperture (w) and slat gap (d) change to match the desired system resolution when given f and ROR are 14 cm and 8 cm respectively. Right plot shows SNR vs. f for the chest-wall lesion when the resolution is 10 mm, which shows very similar pattern when the resolution is 5 mm (Fig. 5(a)).

Fig. 15.
The dependencies of the sensitivity on the resolution.

TABLE I

Geometric parameters of slit-slat and multislit-slat collimator. The parameters that are relevant only to multislit-slat imaging are located at the bottom

Parameter	Description
w	The slit width.
α	The acceptance angle of the slit.
f	The focal length, measured from the slit plane to the detector.
d	The gap between slats.
a	The height of the slats.
t	The thickness of the slats.
p	The fraction of the detector dedicated to the center slit.
s	The distance between the center slit and side slit.

TABLE II

Sampling of angular ranges of the slit-slat collimator at given f and ROR. This table shows only even values of f and ROR. T denotes inaccessible configurations due to breast truncation and R denotes inaccessible configurations due to the system resolution.

	ROR						
f	8 cm	10 cm	12 cm	14 cm	16 cm	18 cm	20 cm
8 cm	141°	159°	R	R	R	R	R
10 cm	138°	168°	180°	192°	R	R	R
12 cm	135°	180°	192°	207°	216°	R	R
14 cm	135°	192°	204°	213°	222°	228°	R
16 cm	T	162°	210°	219°	225°	228°	234°
18 cm	T	159°	216°	222°	225°	228°	234°
20 cm	T	156°	216°	222°	225°	228°	234°

Sampling of angular ranges of the multislit-slat collimator at given f and ROR. This table shows only even values of f and ROR. We selected the values of p and s for 60% and 8 cm, respectively. T denotes inaccessible configurations due to breast truncation and R denotes inaccessible configurations due to the system resolution.

TABLE III

	ROR						
f	8 cm	10 cm	12 cm	14 cm	16 cm	18 cm	20 cm
8 cm	120°	138°	R	R	R	R	R
10 cm	T	132°	153°	162°	R	R	R
12 cm	T	117°	150°	162°	171°	R	R
14 cm	T	105°	132°	162°	171°	183°	R
16 cm	T	T	117°	162°	171°	183°	195°
18 cm	T	T	105°	129°	171°	183°	195°
20 cm	T	T	T	117°	171°	183°	195°