Multi-pinhole SPECT Imaging with Silicon Strip Detectors

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***Abstract*-- We are pursuing the development of small-animal SPECT systems for imaging at low energies (such as iodine-125 emissions) based on silicon double-sided strip detectors together with multiple-pinhole apertures. We have conducted imaging studies of phantoms using a prototype system that utilizes a detector of 300-micrometer thickness and 50-micrometer strip pitch. Good spatial resolution can be achieved with a 23-pinhole aperture at low magnification (~26 mm ROR, ~7 mm aperture-detector separation). A next-generation system is currently under development that will use silicon detectors of greater thickness (1 mm) and active area (~6 cm x 6 cm) deployed in a stacked configuration such that projection data will be acquired at multiple magnifications simultaneously. We expect this system to offer sub-millimeter spatial resolution in combination with good sensitivity.**

I. Introduction

The ability of pinhole SPECT using conventional gamma cameras to achieve the spatial resolution required for small-animal imaging applications has been amply demonstrated over the last decade [1], [2]. Practical applications in small-animal imaging also place demands on the sensitivity of the imaging system, and recently several groups have sought to increase the sensitivity through the use of multiple-pinhole apertures in combination with either conventional gamma cameras [3], [4] or custom-built scintillator cameras [5]. In these approaches magnification of the projected image onto a detector of modest spatial resolution (~1-3 mm) is used to obtain high spatial resolution in the reconstructed images (<1.5 mm).

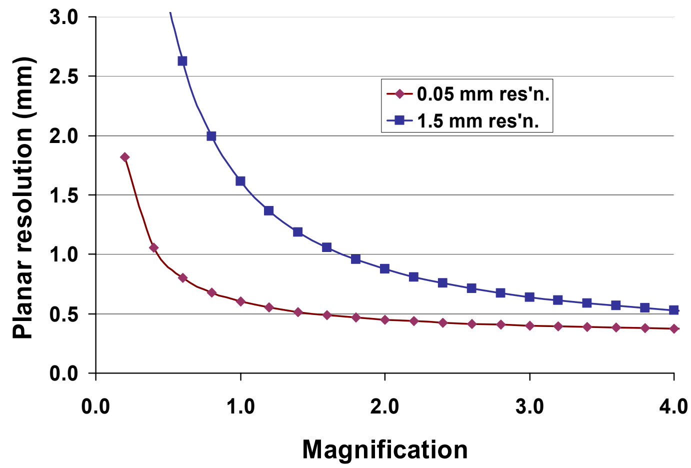

Figure 1. Resolution as a function of magnification for an object 2.5 cm in front of a 300 μm-diameter pinhole. The upper curve is the result if a detector with 1.5 mm spatial resolution is used, while the lower is with a detector of 0.05 mm spatial resolution.

Our approach to multiple-pinhole imaging is to utilize a radiation detector with intrinsic spatial resolution more than an order of magnitude better than these scintillator-based approaches. The chief advantage of such an approach is that equivalent image resolutions can be achieved with much lower magnification. As an example, Fig. 1 shows the planar image resolutions as a function of magnification for an object 2.5 cm from a 300 μm-diameter pinhole for detectors with two different spatial resolutions, where the calculations were done using the standard formula for pinhole planar image resolution [6]. For any given multiple-pinhole configuration, the reduction in the required magnification results in reduced multiplexing of the pinhole projections and a smaller required total detector area.

Previous work has also shown the potential power of combining high spatial resolution detectors with multiple-pinhole apertures in a synthetic-collimator imaging configuration [7]. By collecting projection data at multiple magnifications via variation in the aperture-detector spacing, high-resolution tomographic images can be obtained using iterative reconstruction even in the presence of multiplexing.

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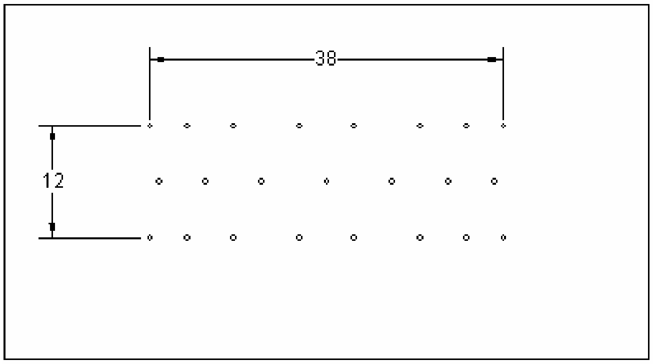

Figure 2. A drawing of the pinhole pattern for the 23-pinhole aperture. The dimensions are in millimeters.

Simulations have further shown that high-quality reconstructions of radiotracer distributions may even be possible when the object is imaged from a single collimator position.

We have chosen to use a silicon double-sided strip detector to demonstrate the potential of this approach. Silicon detectors are a suitable choice for the high-spatial resolution detector needed for a synthetic-collimator imaging system because the technology is well developed, thanks to their use in high-energy physics, and the use of photolithography to pattern the readout electrodes allows manufacture of detectors with strip pitches down to as little as 20 μm. They have not found widespread use in nuclear imaging, however, because they have very low efficiency at the gamma-ray energies typically of interest (i.e. 140 keV). The detection efficiency is useable, however, for the distribution of photon energies emitted in the decay of ^{125}I (27.2-35.5 keV) — about 10% total detection efficiency in 300 micrometers of silicon. Because ^{125}I is widely used in molecular biology, owing to the wide array of molecules that can be easily iodinated and to the fact that its half-life (59.4 days) is convenient for radiolabeling, such a system tailored for the imaging of ^{125}I-labeled tracers is potentially of practical use as well.

II. Prototype System

We have developed a prototype system to demonstrate the potential for high-resolution imaging using silicon detectors together with multiple-pinhole collimation and to explore issues relevant to the design of a fully customized system. The compact nature of the detector and the relative ease of collimating photons in the 30 keV energy range allow easy exploration of different imaging configurations.

A. Silicon Detector and Readout Electronics

The silicon detector used for the prototype imaging system is a 300 μm-thick double-sided strip detector. It has 560 strips on the p-side and 1260 on the n-side, at a strip pitch of 50 μm on both sides. The detector possesses over 700,000 resolvable spatial elements spread over an active area of 28 mm × 63 mm.

The electronics utilize the VaTaGP2.2 application-specific integrated circuit (ASIC), manufactured by IDEAS ASA, Norway (now Gamma Medica-Ideas). Each strip on the detector is wirebonded to a separate channel of a 128-channel ASIC, which provides a preamplifier, shaper amp, comparator, and sample-and-hold circuitry. An external trigger threshold is set for each detector side independently. The ASICs also have internal 3-bit trim DACs that can be used to vary the trigger level for each channel individually with respect to the applied threshold to attain better triggering uniformity. Individual noisy strips can be disabled, eliminating this possible source of spurious events from the data stream. The entire readout is event-driven with a sparse readout that presents the address of the strip that triggered the readout, the pulse height of that channel, and the pulse heights of its nearest neighbors. The data acquisition is controlled by three field-programmable gate arrays (FPGAs), one for each detector side plus a master FPGA. List-mode data is passed from the master FPGA to the host PC through a National Instruments data-acquisition PCI card.

B. Multiple-Pinhole Apertures

We have chosen to use molybdenum for our collimator material because its K-edge at 20 keV results in a high attenuation factor over the energy range of interest. Consequently, a 500 μm-thick piece is sufficient for use as an aperture for imaging emissions from ^{125}I decay. While we previously utilized apertures with high-precision pinholes fashioned using electron-discharge machining [8], we have developed a technique for making apertures using micro-drill bits that enables rapid, inexpensive production of imaging apertures. Drilling a hole with a 300-μm drill bit and then drilling partway through with a 500-μm drill bit results in a pinhole that provides a reasonable approximation of a single knife-edge with a full opening angle of 76º. Fig. 2 shows the layout for a 23-pinhole aperture produced using this technique.

III. Imaging Studies

We have performed imaging studies utilizing the 23-pinhole aperture shown in Fig. 2 to image a phantom consisting of several glass capillary tubes (1.1 mm I.D.) filled with a solution of Na^{125}I and inserted into holes drilled in a 25.4 mm-diameter polycarbonate cylinder. The total activity in the phantom was approximately 1 mCi. The purpose of the cylinder was to simulate an attenuating medium similar in size and density to a mouse.

Projection data were collected for one hour each at eight angular positions, each separated by 45 degrees, and two magnifications. The aperture-to-detector distances were 6.7 mm and 13.7 mm, and the radius of rotation was 25.8 mm.

Prior to image reconstruction, the projection data were downsampled to 200 µm-isotropic effective detector pixel size to reduce the impact of nonfunctioning detector strips and efficiency variations. An image of one set of projection data acquired at the smaller magnification is shown in Fig. 3 after this downsampling. A single transverse slice of the reconstructed image after 10 iterations of maximum-likelihood expectation-maximization reconstruction is shown in Fig. 4, alongside a schematic view of the phantom. The reconstructed slice shown in Fig. 4 utilized only the projection data collected at the lower magnification. Fig. 5 shows the same slice from a reconstruction done using only data from the larger magnification on the left, as well as a reconstruction done using all of the projection data. The center-to-center spacing of the capillaries in the upper "V" was 2.5 mm.

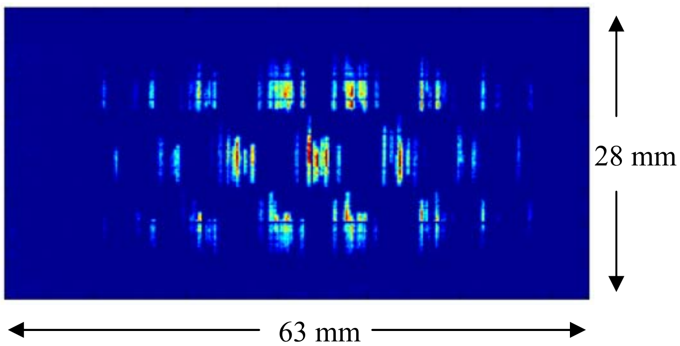

Figure 3. An example of the projection data acquired at the lower magnification with the dimensions of the silicon detector indicated.

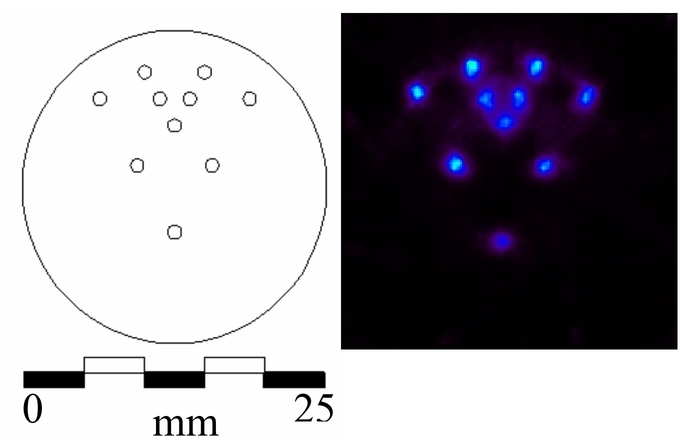

Figure 4. A cross-sectional schematic of the phantom with length scale indicated (left), and a single transverse slice of the image reconstructed using only data acquired at the lower magnification (right).

While the hot spots are quite well resolved in all cases, it is apparent that the best combination of spatial resolution and contrast is achieved in the reconstruction utilizing the full projection data set. We also investigated the ability to perform

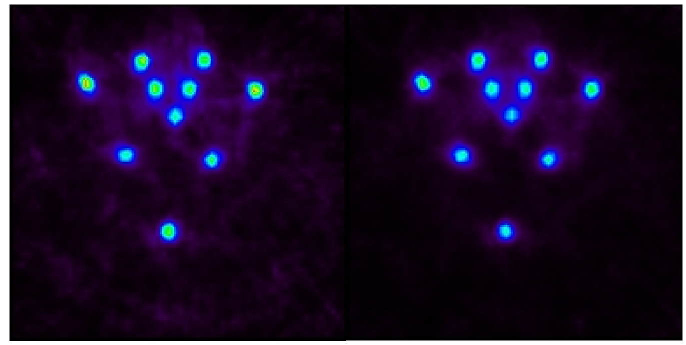

Figure 5. Transverse slices from reconstructions performed using only data from the larger magnification (left) and from all projection data (right).

tomographic reconstructions utilizing only a subset of the angular views. The left of Fig. 6 shows a transverse slice of the reconstruction done using only data acquired at two projection angles separated by 90 degrees, but including both magnifications. While the image quality is somewhat degraded relative to reconstructions done using data from all projection angles, it is largely free of serious distortions or artifacts. In contrast, the reconstruction shown on the right in Fig. 6 that used data from both magnifications but only a single projection angle shows poor resolution in the direction moving away from the aperture-detector assembly, as is typical of such limited-angle tomography schemes.

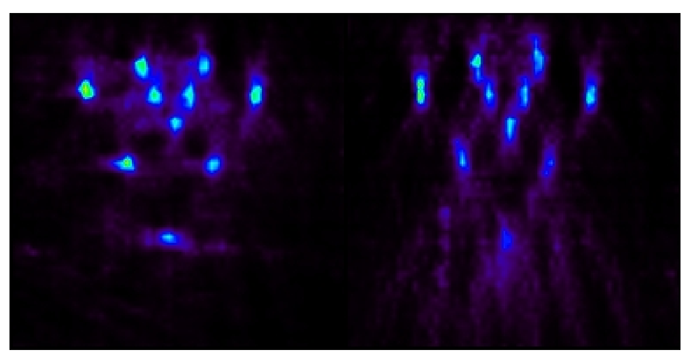

Figure 6. Transverse slice from reconstructions performed using data from both magnifications but only two viewing angles separated by 90° (left) and only a single viewing angle (right).

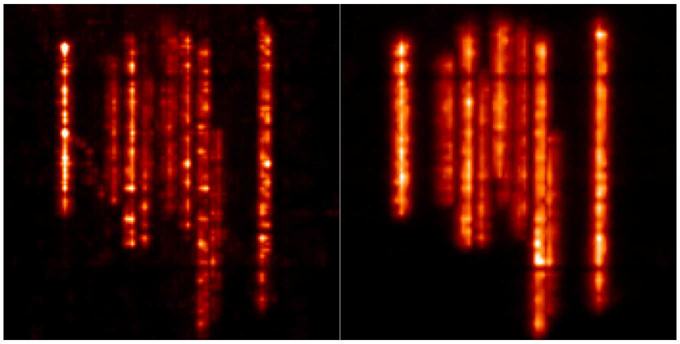

Figure 7. Reprojected planar views created from tomographic reconstructions using only data acquired from a single angle (left) and data from all angles (right).

One of the original motivations for the synthetic-collimator imaging approach was to synthesize ideal planar projections free of the depth-dependent resolution degradation from which parallel-hole collimation suffers. To investigate the capabilities of the prototype system in this regard, the tomographic reconstruction shown on the right in Fig. 6 was reprojected in a plane parallel to the aperture. This synthesized planar image is shown on the left in Fig. 7. For comparison, a reprojection of the reconstruction done using the full data set (Fig. 5, right) is shown on the right in Fig. 7. The planar image created from the single viewing angle shows greater intensity variations in the vertical direction due to uncorrected variations in detector efficiency, but otherwise is of high quality.

IV. Current and Future Work

We are in the process of obtaining a new set of detectors and electronics to improve upon the imaging system. The new silicon detectors will be both thicker and larger in area. The greater thickness will improve the detection efficiency, while the increased area will allow us to incorporate a larger number of pinholes into the system. The new system will incorporate four detectors, allowing multiple magnifications to be obtained simultaneously, as well as multiple viewing angles. Based on the current work and previous simulations, it may be possible to reconstruct high-resolution, artifact-free images with such a system without motion of either the imaging system or subject. Table I presents a comparison of the detectors for the prototype and new systems. One possible arrangement for imaging with the new detectors is depicted in Fig. 8.

TABLE I
DETECTOR DETAILS FOR THE CURRENT AND FUTURE SYSTEMS

	Thickness	^{125}I efficiency	Active Area	# of Detectors
Prototype	300 µm	~10%	29×63 mm^2	1
2nd Generation	1 mm	~29%	~60×60 mm^2	4

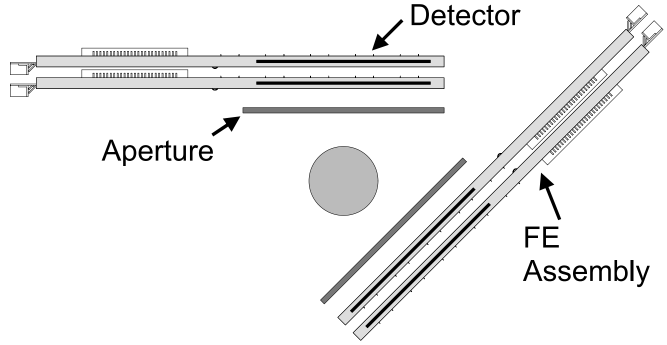

Figure 8. A schematic view of one possible imaging configuration for the system with four silicon detectors.

The work done thus far with the prototype system has involved little or no multiplexing of the pinhole projections on the detector. With the new system we will explore the impact of allowing greater multiplexing in the higher-magnification data. We also plan to investigate the use of tilted pinholes to improve the sampling within the field of view while more fully utilizing the available detector area. Altogether, the improvements in the 2nd generation system are expected to offer around a 25-fold improvement in system sensitivity over the prototype system.

V. Conclusions

We have demonstrated the ability to perform tomographic reconstructions of multi-pinhole data acquired at multiple magnifications using a silicon double-sided strip detector of high spatial resolution. We have also explored the ability to reconstruct images using data from a small number of views using our prototype imaging system. We believe this approach is well suited for imaging applications requiring high spatial resolution over a small field of view, such as mouse brain imaging. Work has begun on a fully customized system that will significantly improve system sensitivity. The use of multiple detectors and multiple imaging heads should also improve the quality of the reconstructed images.

VI. Acknowledgment

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VII. References

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