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Original paper

Spinning slithole collimation for high-sensitivity small animal SPECT: Design and assessment using GATE simulation

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ABSTRACT

Purpose: While traditional collimations are widely used in preclinical SPECT imaging, they usually suffer from possessing a low system sensitivity leading to noisy images. In this study, we are aiming at introducing a novel collimator, the slithole, offering a superior resolution-sensitivity tradeoff for small animal SPECT.

Methods: The collimator was designed for a molecular SPECT scanner, the HiReSPECT. The slithole is a knife-edge narrow long aperture extended across long-axis of the camera's head. To meet the data completeness requirement, the collimator-detector assembly spins at each regular SPECT angle. The collimator was modeled within GATE Monte Carlo simulator and the data acquisition was performed for NEMA Image Quality (IQ) phantom. In addition, a dedicated 3D iterative reconstruction algorithm based upon plane-integral projections was also developed.

Results: The mean sensitivity of the slithole is 285 cps/MBq while the current parallel-hole collimator holds a sensitivity of 36 cps/MBq at a 30 mm distance. The slithole collimation gives rise to a tomographic resolution of 1.8 mm compared to a spatial resolution of ~1.7 mm for the parallel-hole one (even after resolution modeling). A 1.75 reduction factor in the noise level was observed when the current parallel-hole collimator is replaced by the slithole. Furthermore, quantitative analysis proves that 3 full-iterations of our dedicated image reconstruction lead to optimal image quality. For the largest rod in the NEMA IQ phantom, a recovery coefficient of ~0.83 was obtained.

Conclusion: The slithole collimator outperforms the current parallel-hole collimation by exhibiting a better resolution-sensitivity compromise for preclinical SPECT studies.

1. Introduction

SPECT scanner design is always challenged by the well-known resolution-sensitivity relationship [1]. In other words, spatial resolution of a SPECT scan improves at the cost of a reduction in sensitivity. In molecular SPECT, the problem is more challenging since the use of high-resolution collimators automatically trades the spatial resolution off against the detection efficiency [2–6]. Therefore, the need for simultaneous high-resolution high-sensitivity SPECT systems mandates to design novel collimation systems exhibiting a different resolution-sensitivity compromise [7–10]. Dynamic cardiac/pulmonary SPECT imaging, low-dose examinations, motion artifact-free scans, and tracer kinetic analysis by parametric image reconstruction in small animal studies require such a high-resolution high-sensitivity camera.

Several SPECT prototypes have been designed and introduced with a high-sensitivity based on planar projections using rotating slat collimators for clinical studies [11–21] with comparable performance with conventional parallel-hole collimators in terms of spatial resolution and lesion detectability, but with much higher detection efficiency. More specifically, Lodge et al. [16], as pioneers of this field of study, gained 12–28 times greater detection efficiency while maintaining spatial resolution (1.6 cm). Early scanners [10–18] utilized a filtered backprojection (FBP) technique for image reconstruction. Due to noise amplification nature of the FBP methods and their produced streak artifact, a set of fully 3D maximum-likelihood expectation-maximization (MLEM) family iterative reconstruction algorithms have been introduced [20,21]. Complexity of these fully 3D reconstruction methods along with their computation expense of system matrix derivation are still

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challenging problems [21]. Translation of the rotating parallel-slat collimators from clinical researches into preclinical studies was also promising [22,23]. An alternative to the parallel-slat collimators in small animal SPECT scanning, is slit collimation. The concept of slit collimation was initially implemented to a preclinical scanner equipped with solid-state strip detector and utilizing analytic image reconstruction methods [24]. Though, the slit collimator's performance was encouraging, but it is hampered by lack of both a fast high-quality iterative reconstruction algorithm and in-detail collimator modeling and imaging physics during simulations [24].

In this work, a novel simultaneous high-resolution high-sensitivity collimator, called the slithole, is designed for the HiReSPECT – a high-resolution small animal SPECT scanner [25–30]. As the slithole deals with plane-integral data (rather than line-integral data in traditional collimators), it requires a sophisticated data acquisition strategy as well as a dedicated image reconstruction algorithm. The present work is first directed towards the optimal design of the slithole and then to assess its performance using various phantom reconstructions utilizing an in-house fast MLEM-based [31] algorithm. Finally, a fair comparison with the current parallel-hole collimator is made considering the same acquisition time.

2. Materials and methods

2.1. The HiReSPECT camera

The HiReSPECT scanner is a two-headed high-resolution SPECT camera, equipped with a low-energy high-resolution (LEHR) lead parallel-hole collimator (1.2 mm hexagonal holes, 34 mm length, and 0.2 mm septal thickness), a 2D pixelated CsI(Na) crystal ($1 \times 1\ \text{mm}^2$ pixel area and 0.2 mm Epoxy gap) as well as two position-sensitive photomultiplier tubes (PSPMTs). Field-of-view (FOV) of the camera is 50 mm × 100 mm. Fig. 1 illustrates the camera and some of its key components.

The gantry of the HiReSPECT' camera routinely rotates around 180° with 32 stops (total 64 projections over 360°). Imaging time at each stop is 60 s. The SPECT images are iteratively reconstructed using a standard rotation-based resolution-modeled ordered-subset expectation-maximization (OSEM) algorithm [28]. It should be highlighted that the HiReSPECT scanner is capable of rotating each head about their 3own axis, allowing the so-called spin rotation.

2.2. The slithole

A 3D schematic view of the slithole collimator is shown in Fig. 2. The slithole is a dual knife-edge aperture embedded in a tungsten body. Table 1 gives geometry specifications of the slithole. Inherent to the geometry of the slithole, it accepts much more photons and therefore can potentially offer a higher detection efficiency than a parallel-hole collimator can. To guarantee a sufficient measurement of the tomographic data, the collimator-detector pair has to

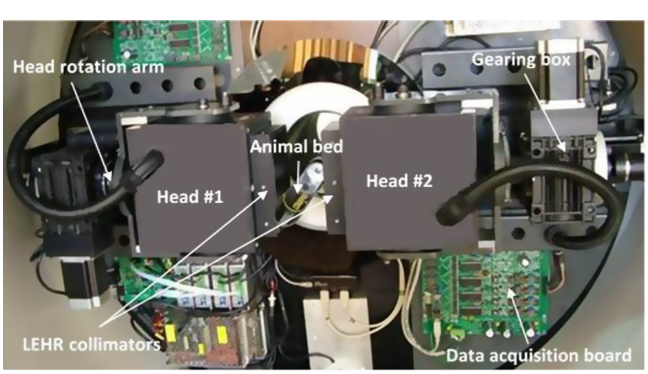

Fig. 1. A close-up view of the HiReSPECT scanner. The HiReSPECT is a dual-headed gamma camera designed for molecular SPECT.

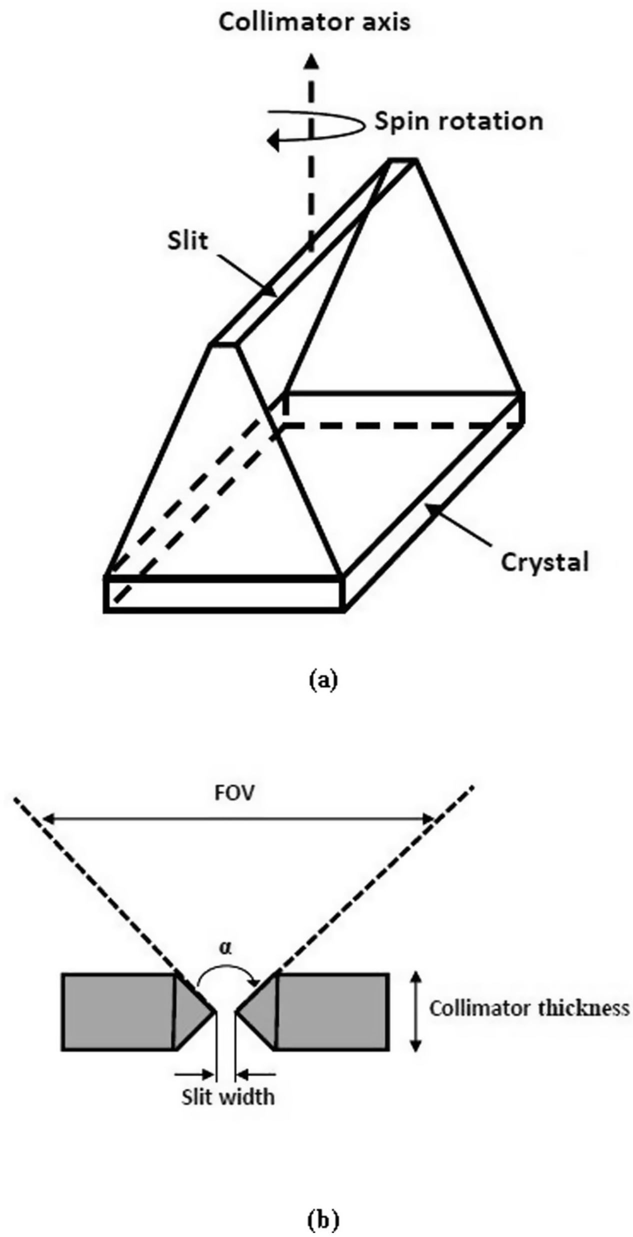

Fig. 2. (a) A 3D schematic view of the spinning slithole collimator, (b) the slithole's edge.

Table 1
The characteristics of the slithole collimation used for the HiReSPECT camera.

Parameter	Specification
Slit width	0.6 mm
Focal length	45 mm
Opening angle (α)	58°
Edge type	Knife-edge
Material	Tungsten
Thickness	2.5 mm
Common FOV	~35 mm at 30 mm ROR