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Performance Assessment of a Channel Multi-pinhole Collimator for Myocardial Perfusion Imaging with SPECT: A Monte Carlo Simulation

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ABSTRACT

While conventional parallel-hole collimators are widely used in myocardial perfusion imaging (MPI) with SPECT, they are suboptimal in balancing the existing sensitivity-resolution compromise. Therefore, multi-pinhole collimation has been proposed to address the problem. In the present study, a channel multi-pinhole collimated SPECT scanner is modeled and then simulated using GATE Monte Carlo simulation. The multi-pinhole collimator comprises eight apertures. The material, diameter, and height of the apertures were assumed to be varying. A comparison with a conventional single-pinhole was also conducted. The results show that increasing the hole diameter leads to degraded spatial resolution for the multi-pinhole collimator. Compared to single-pinhole collimators, multi-pinhole collimators suffer from projection overlapping and thus deteriorated spatial resolution. The findings confirm that the channel multi-pinhole collimators outperform the single-pinhole apertures by providing much higher sensitivity at the expense of slightly lower spatial resolution and therefore would be the collimator of choice for MPI with SPECT.

Keywords: SPECT; Monte Carlo; GATE; MPI; Multi-pinhole

1. Introductions

Cardiovascular diseases (CVDs) are the most common heart condition and a major cause of death across the globe [1]. According to a recent World Health Organization report [1], 17.9 million deaths due to CVDs were expected in 2021. Myocardial perfusion imaging (MPI) is a diagnostic task and an important imaging modality that evaluates many CVDs, such as hypertrophic cardiomyopathy, and coronary artery disease [2]. MPI using single-photon emission computed tomography (SPECT) is the most commonly performed procedure for the evaluation of patients with

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suspected or known CVD across the world. SPECT, by detecting gamma rays emitted from injected radioisotopes into the human body, is a nuclear imaging modality where two- or three-dimensional (2D/3D) images are obtained [3]. The SPECT scan is influenced by several factors including scattering and attenuation of gamma-rays, collimator geometry, and so on [4].

Among many components constituting a SPECT camera, the collimator plays a pivotal role and mainly affects the image quality. This is because it controls the resolution, noise, and sensitivity of the final functional image [5]. While parallel-hole collimation is routinely used for cardiac SPECT imaging, there is no clinically-demanded resolution-sensitivity balance for simultaneously high-resolution and high-sensitivity imaging [6]. Pinhole collimation has therefore been proposed to address the challenge. Because of its excellent spatial resolution, the pinhole collimator is used to image small animals, small organs, and small regions of interest, such as the thyroid and heart [7-8]. The multi-pinhole collimator was introduced as an alternative to single-pinhole collimators to increase sensitivity while maintaining spatial resolution [5]. A multi-pinhole collimator has several pinhole apertures in which increasing the number of holes improves the sensitivity [7].

Monte Carlo (MC) simulation plays a key role in the design and optimization of medical imaging systems, especially in computed tomography (CT), SPECT, and positron emission tomography (PET) [4,9]. Various MC toolkits such as GEANT4, MCNP/MCNPX, and GATE have been used for simulations of this type, each with a variety of capabilities [5]. The GATE simulator is based on the GEANT4 toolkit and is dedicated to medical physics applications like diagnostic imaging, nuclear medicine imaging/dosimetry, brachytherapy, and radiation therapy [10-11]. GATE is also freely available and benefits from valid physics libraries and several post-processing tools [9].

This work aimed to evaluate and assess a heart-dedicated keel (channel)-edge multi-pinhole collimator for MPI with SPECT using accurate GATE MC simulation. The influence of collimator material on its performance was also investigated. Furthermore, a comparison with single-pinhole collimation was also conducted to study the effect of projection overlapping in the designed multi-pinhole collimator.

2. Materials and Methods

The scanner

A cardiac SPECT scanner enabling MPI was designed and MC modeled. The scanner consists of a multi-pinhole collimator coupled with a monolithic 10 mm-tick NaI (Tl) detector. Key technical specifications of the scanner are listed in Table 1. For a fair comparison, the multi-pinhole collimator was replaced with a single-pinhole one. For both cases, the hole diameter, keel height, and collimator material were assumed to be varying.

Table 1. Geometric characteristics of single- and multi-pinhole collimators.

Specification	Single-pinhole	Multi-pinhole
Detector area (mm^2)	200 × 140	200 × 140
Number of apertures	1	8
Hole diameter (mm)	0.5-4.0	0.5-4.0
Keel height (mm)	0, 1.0, and 2.0	0, 1.0, and 2.0
Opening angle (degree)	60	50
Collimator depth (cm)	14.0	5.0
Material	Pb, W, and Au	Pb, W, and Au

The collimator was made of lead, gold, and tungsten. The aperture diameter and keel height were assumed to be 0.5, 1.0, 2.0, 3.0, and 4.0 mm, and zero (no channel), 1.0, and 2.0 mm, respectively. All apertures were focused toward the center of the field-of-view (FOV). Figure 1 shows schematics, not to scale, of the single- and multi-pinhole collimators. To avoid large projection overlapping (multiplexing) over the detector in multi-pinhole collimation, the distance between the collimator and detector was reduced. To perform a fair comparison, the spatial resolution of the single-pinhole collimator was corrected for the distance between the collimator and detector.

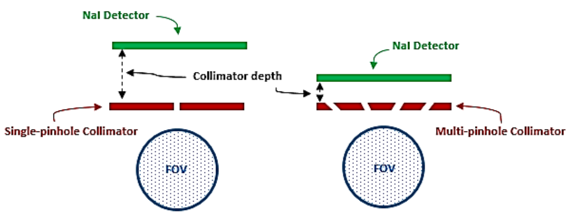

Fig. 1. A schematics (not to scale) of the single- (left) and multi-pinhole (right) collimators.

GATE Monte Carlo Simulation

GATE version 8.2, for the various single- and multi-pinhole configurations, was performed to evaluate and compare their performance. The statistical uncertainties of the MC simulations were below 2.0%. A spherical water phantom mimicking the normal heart containing a 10 mCi Tc-99m point source at its center was simulated. The spatial resolution of the projection image was calculated in terms of full width at half-maximum (FWHM). Three conventional collimator materials (gold, lead, and tungsten) with varying hole diameters were compared and the GATE simulations were then repeated. Modeled radiation physics includes photoelectric absorption, Compton scattering, pair production for photons and Bremsstulung, ionization, and multiple scattering for electrons. An energy window of 20% was applied to all simulation data. A data acquisition period of 5.0 min was considered. The intrinsic spatial/energy resolution of the NaI (Tl) detector was also taken into account.

3. Results and Discussion

Figure 2 exhibits the impact of the collimator material on the spatial resolution of the multi-pinhole collimated scanner for various hole diameters. The collimator material contributes to edge penetration and scattering and therefore results in the degradation of the spatial resolution. The gold affords a superior performance by exhibiting the lowest FWHM across all hole diameters. It is clear from Figure 2 that increasing the hole diameter leads to degradation of the spatial resolution. Despite the higher cost, gold outperforms conventional materials used in SPECT scanners in terms of scattering and penetration. Gold exhibits a higher linear attenuation coefficient than lead and tungsten at 140 keV. It is worth noting that gold is also being utilized in a number of small-animal SPECT scanners around the world [7].

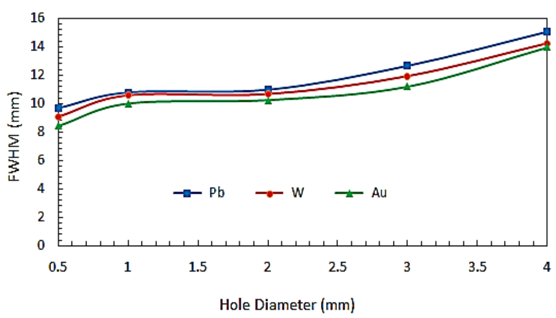

Fig. 2. Spatial resolution of the multi-pinhole collimator as a function of hole diameter for three conventional collimator materials.

Figure 3 shows the influence of keel height on the spatial resolution of the multi-pinhole collimated scanner. Referring to Figure 3, it is clear that an increase in keel height leads to improved spatial resolution. The reason can be explained by that the larger the keel height, the lower the edge penetration. Therefore, for high-resolution imaging tasks, the channel multi-pinhole collimators offer promising results across all keel heights. Compared to the rest of the materials, gold provides lower penetration and scattering. Notably, a zero keel height corresponds to traditional knife-edge apertures.

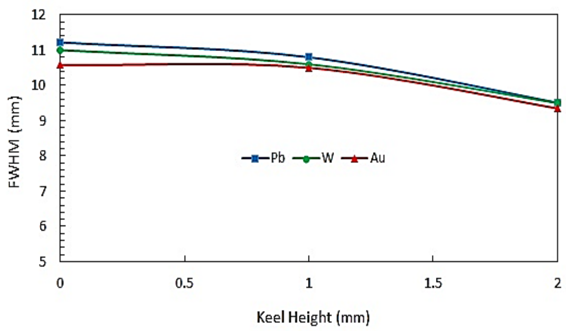

Fig. 4. Spatial resolution of the multi- and single-pinhole collimators as a function of hole diameter. The collimator material is gold.

4. Conclusion

An in-depth comparison of the single- and multi-pinhole collimators for a cardiac SPECT scanner has been conducted. Although both single- and multi-pinhole collimations provide high spatial resolution compared to conventional parallel-hole collimators, the multi-pinhole collimations outperform the single-pinhole by providing improved sensitivity while preserving the spatial resolution at a clinically acceptable level. The future work of this study will be the utilization of voxelized phantoms/sources and tomographic reconstruction of the images.

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