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MRC-SPECT: A sub-500 μm resolution MR-compatible SPECT system for simultaneous dual-modality study of small animals

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Abstract

In this paper, we will report the development of an ultrahigh resolution MR-compatible SPECT system that can be operated inside a pre-existing clinical MR scanner for simultaneous dual-modality imaging of small animals. This system is constructed with 40 small-pixel CdTe detector modules assembled in a fully stationary ring SPECT geometry. We have experimentally demonstrated that this system is capable of providing an imaging resolution of $<500\ \mu\text{m}$ when operating inside MR scanners. We will report the design, construction of the MRI-compatible SPECT system, including the detector technology, collimator, system development and so on. The first imaging results obtained with this newly constructed SPECT system will also be reported.

Keywords

MR compatible SPECT; CdTe/CZT; Hybrid pixel-waveform readout; System development

1. Introduction

In recent years, multi-modality imaging systems are playing important roles in clinical and research applications by delivering simultaneous achieved anatomical and functional information. Among these modalities, combined MRI and nuclear imaging systems such as MR/PET and MR/SPECT have shown great potential and drawn substantial research and development effort. The MRI could provide the anatomical structures of particular organs, tissues or cells with much better soft tissue contrast than that of conventional X-ray CT, and the nuclear imaging techniques are capable of following functional metabolism of them over time in normal or diseased condition. We have previously developed a sub-500 μm resolution prototype MR compatible SPECT system based on the first generation energy-resolved photon-counting (ERPC) CdTe detectors [1]. It offers spatial resolution of 350 μm and energy resolution of 3–4 keV. To obtain an accurate reconstruction of the source object inside MR scanner, we have also developed a comprehensive charge collection model inside strong magnetic field to precisely derive the system response function which is the key to achieve high resolution image inside MR [2].

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Based on previous efforts, we are currently constructing an ultrahigh resolution stationary MR compatible SPECT (MRC-SPECT) system for small animal imaging based on second-generation ERPC detectors. A full ten-head detector ring has been assembled to deliver a state-of-art MR compatible SPECT system with sub-500 μm spatial resolution and a reasonable sensitivity. Detailed system design and the first imaging result with this system will be reported in this paper.

2. Method

2.1. The generation-II ERPC detectors

The ultrahigh resolution MR-compatible SPECT system is built around a small-pixel CdTe detector module that we have recently developed (Fig. 1). Each module consists of CdTe detectors having an overall size of $22.5 \times 11.2 \times 2 \text{ mm}^3$, divided into 64×32 pixels of 350 μm in size. We have previously reported the performance of the first generation ERPC ASICs in [1]. The ASICs in the Gen-II ERPC detectors allow for a much lower low energy threshold, and incorporates three gain levels for handle different gamma ray energies. The excellent energy resolution, high spatial resolution as well as MR compatibility ensures the Gen-II ERPC detector to provide promising imaging performance. The detector is read out with a novel hybrid pixel-waveform readout system that is designed to alleviate several challenges for using small-pixel CdTe detectors in ultrahigh-resolution SPECT imaging applications. The HPWF system utilizes a modified version of a 2048-channel 2-D CMOS ASIC to readout the anode pixel, and a digitizing circuitry to sample the signal waveform induced on the cathode [3]. The cathode waveform acquired with the HPWF circuitry offers excellent spatial resolution, energy resolution and DOI information, even with the presence of excessive charge-sharing/charge-loss between the small anode pixels. The depth of interaction can be derived by electron and hole drifting time. To ensure the MR-compatibility, we have minimized the use of magnetic components during the HPWF CdTe detector development. Every detector is attached to an air channel embedded base plate mounting to the supporting frame shown on Fig. 1.

2.2. MRC-SPECT system development

This ultrahigh resolution MR compatible small animal SPECT system consists of ten second-generation ERPC detectors assembled as a compact ring. The SPECT system is installed on a non-metal gantry constructed with 3-D printing using nylon powder material. This technique is highly flexible that allowed us to integrate air pipes for detector cooling and channels for electrical wiring into a single-piece construction. Fig. 2 is the system design drawing which contains the detector rings, system housing, pinhole aperture, system control electronics PCB board, front and rear cover, etc. A single detector ring consists of ten detectors and we can put two detectors rings together to get larger field of view, large sensitivity and more sufficient angular sampling. The distance between the opposite detectors is 15.6 cm and the detection area of each detector is $22.5 \times 45 \text{ mm}^2$. Each detector has four 300 or 500 μm pinholes and the object to pinhole distance is designed to be around 36 mm. The object can be transmitted into the cylindrical lead aperture tube from the front side under control of precise linear motors.

In order to control the operation of the ten ERPC detector modules, we have also developed a central control unit as shown in Fig. 3. The control PCB provides 12 regulated power supply channels and 12 independent data channels for sending the digital data acquired by the detectors to a host PC (through USB2). The current readout system is capable of reading out up to 1000 frames per second, which allows for a dynamic data acquisition with accurate time stamp. All the detector components, pinhole apertures, as well as other external parts have minimized MR susceptible materials to ensure system MR compatibility.

2.3. Collimator design and system response function derivation

In order to achieve sub-500 μm imaging resolution, we have constructed two SPECT apertures, with different pinhole sizes of 300 μm and 500 μm respectively. The inner diameter of the lead tube is 66 mm and the tube thickness is 16 mm. It has pinhole inserts that are made of cast platinum (90%)-iridium (10%) alloy, which provides the maximum stopping power and are compatible with MR scanners. The opposite detectors are placed 15.6 cm apart and the magnification factor of this SPECT system is around 1.2. A total of 40 pinholes will be used in the 10 detector ring system and the sensitivity can achieve up to 0.07%. In particular, four 300 or 500 μm diameter pinholes are used for each detector and all pinholes are inserted in the cylindrical lead aperture tube as a ring. The pinhole open angle is 501 and the height is 6 mm. As shown in the Fig. 4, the aperture is specifically designed to prevent severe pinhole projections. The design rule is that projections through each pinhole will be constrained in two neighboring detector hybrids. The designed field of view of this system is about $\phi 2 \times 2 \text{ cm}^2$. In future studies, we can also use apertures of smaller inner diameter (larger magnification) to investigate the imaging performance.

To calculate precise system response function, we have previously developed a mathematical model to mimic the pinhole aperture as multiple layers of thin sheets [4]. A comprehensive geometry calibration routine has been applied to derive accurate geometry information. In particular, a Co-57 point source is used to scan the object space. The experimental point source projections acquired with ten detectors are used for geometry calibration. To deliver simultaneous MR and SPECT imaging, a birdcage RF coil can be transmitted into the lead aperture tube and the source object will be place inside the RF coil.

3. Results

3.1. The fully-working MRC-SPECT system

Fig. 5 shows the assembled fully-working MRC-SPECT system. Ten detectors are closely packing around the system housing. A carbon-fiber made animal holder is mounted on precise 3-D motors ((Newport MFA-CC)) to transport the imaging object. The system can be operated on a laboratory bench as an ultrahigh resolution stationary SPECT microscope. This compact system can also be operated inside a pre-existing MR scanner. The system housing outer diameter is 248 mm and the MR bore diameter is 350 mm in this figure. It is worth pointing out that all the ten detectors have remarkable uniformity performance. Fig. 6 represents the gain map throughout the ten detectors and the dead-pixel number is below 0.05%. The energy resolution for individual pixels is about 4–6 keV.

3.2. Preliminary imaging results

We first used a point source phantom to demonstrate the imaging performance of MRC-SPECT. In this study, a Co-57 point source is controlled by precise linear motors to generate a regular-triangular shape phantom. The active area of the point source is 250 μm in diameter and the activity is around 70 μCi . The distance between the neighboring point source can be adjusted by choosing different motor movement step size as shown in Fig. 7. The 500 μm features can be easily resolved with 500 μm pinholes. The 350 μm features are also quite clear using 300 μm pinholes. We also carried out lab made Jaszczak phantom study filling with 1 mCi Tc99m. The PTFE phantom has four sets of hot rods, with diameters of 1000 μm , 750 μm , 500 μm and 350 μm , correspondingly. The 500 μm features are clearly resolved and we can almost see the smaller features. The two sets of imaging studies are both carried out outside the MR field. We have previously investigated the imaging performance of a prototype rotational MRC-SPECT system inside MR scanner [2] and we will investigate this stationary system imaging performance inside the MR scanner in the near future. The comprehensive modeling of system response function will be applied to get decent SPECT image in strong magnetic field.

4. Conclusions

In this paper, a stationary MR compatible small animal imaging SPECT system development and preliminary imaging performance is presented. The MRC-SPECT is based on up to twenty generation-II energy-resolved photon-counting detectors. Each detector is associated with four pinholes in average. Detailed system design and construction process has been discussed. This compact system can work as either a bench top ultrahigh resolution SPECT system or a dual-modality MR-SPECT system with sub-500 μm spatial resolution. Preliminary imaging studies have demonstrated the ultrahigh resolution imaging capability of this system. In the future, a series of phantom and small animal imaging studies will be carried out to further evaluate the MRC-SPECT system developed in University of Illinois.

References

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Fig. 1.
The Gen-II MR-compatible detector module used in the MRC-SPECT system.

Fig. 2.
The MRC-SPECT system 3-D drawing and description.

Fig. 3.
System level circuit board (12 channels, power feed and data communication).

Fig. 4. The collimator and pinhole inserts fabricated for MRC-SPECT. (a) and (b): the Pt/Ir pinhole inserts with 300/500 μm diameter pinhole. (c) The actual MRC-SPECT aperture assembly.

Fig. 5.
Up: the ultrahigh resolution SPECT-MR system recently developed. Left represents the system installed inside a pre-existing MR scanner. Down: the desktop MRC-SPECT system.

Fig. 6. Measured pixel gain map through all the detectors, which demonstrates remarkable uniformity of the imaging system. The dead-pixel count is below 0.05% of all pixels.

Fig. 7.

(a) The generated point source phantom used in experimental studies. (b) Experimentally acquired phantom image with apertures with 500 μm pinholes. (c) Phantom image acquired with the 300 μm pinhole aperture. (d) Lab made Jaszczak phantom filled with 1 mCi Tc-99m (30 min).