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First imaging result with an ultrahigh resolution stationary MR compatible SPECT system

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Abstract

In this paper, we will present the design and preliminary performance of an ultrahigh resolution stationary MR compatible SPECT (MRC-SPECT) system that is developed in our lab. The MRC-SPECT system is based on the second-generation energy-resolved photon-counting (ERPC) CdTe detectors and there are several key features associated with this system. Firstly, up to a total of twenty ERPC detectors will be assembled as a very compact ring, which provides an adequate angular sampling capability and a relatively high detection efficiency. The detectors are supported on a gantry made of high strength polyamide structure constructed using 3-D printing. This compact system can be directly operated inside an MR scanner. The detector module used in this system offers an intrinsic resolution of 350 μ m and an excellent energy resolution of around 3~4keV. Each ERPC detector module consists of four pixelated CdTe detectors with a total dimension of 4.5cm $\times$ 2.25cm. Secondly, a die-cast platinum pinhole inserts and cast lead apertures are developed for this stationary SPECT system. Four 300/500 μ m diameter pinholes are used for each detector and all pinholes are mounted around a casted cylinder lead aperture tube. The inner diameter of the lead aperture tube is 6cm and the lead tube thickness is 16mm. The opposite detectors are placed 15.6cm apart and the magnification factor of this SPECT system is about 1.2. Thirdly, a comprehensive charge collection model inside strong magnetic field has been developed to account for the magnetic field induced distortion in the SPECT image. This model can accurately predict the detector's energy and spatial response to gamma ray incident events and then help to compensate for the event position recording error due to the strong magnetic field. In this development, we have made an effort to minimize the amount of magnetic materials in the system to alleviate potential interference to magnetic field inhomogeneity.

I. INTRODUCTION

Multi-modality imaging systems is playing an important role in recent clinical and research applications. Combined MRI and nuclear imaging systems such as MR/PET and MR/

SPECT have shown great potential and drawn substantial research effort in the past few years. 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. Extensive efforts have been devoted to the development of MR/PET system. Comparing to the MR/PET, the development of MR/SPECT is lacking to some extent, mainly due to the stringent requirements on MR compatible SPECT detectors and the interference between these two imaging modalities. Meier *et al.* have reported an MR-compatible SPECT system based on CZT detectors [1] and an MRSPECT system is developed by Hamamura *et al.* [2]. We have previously developed a sub-500 μ m resolution prototype MR compatible system based on the first generation energy-resolved photon-counting (ERPC) CdTe detectors [3-4]. It offers spatial resolution of 350 μ m and energy resolution of 3-4keV. To obtain an accurate reconstruction of the source object, 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 [4].

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

II. MATERIALS AND METHODS

A. Stationary MR Compatible SPECT System Design

This ultrahigh resolution MR compatible SPECT system consists of up to twenty second-generation ERPC detectors assembling as a compact ring. Figure 1 shows the current system design that contains a ring detectors, 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 15.6cm and the detection area of each detector is 22.5 mm $\times$ 45mm. Each detector is (in average) coupled to four 300 or 500 μ m pinholes and the object to pinhole distance is designed to be 33mm. Ten detectors are mounted on a non-magnetic supporting frame, as also shown in Fig. 1. Every detector has a dedicated air channel embedded in the base plate mounting to the supporting frame shown in figure 1. The object can be translated into the cylindrical lead aperture tube from the front side under control of a precise linear motor.

Figure 2 shows two other important components of the system, the rear cover and the system PCB. The power and high voltage supply, communication and data transfer cables, and air cooling facilities will come through the rear cover neatly. A hollow is buried in the rear cover, which helps to provide uniform and continuous airflow for ten air channels. The whole system can be stationary operated on a laboratory bench working as an ultrahigh resolution SPECT microscope. It is also portable since the system is very compact, based on

which assembling this system inside a pre-existing MR scanner is relatively straightforward. All the detector components, pinhole apertures, as well as other external parts are constructed with a minimum amount of magnetic materials to ensure system MR compatibility. Based on this system, two rings of detectors can be used to form a ring of 4.5 cm in axial length as shown in Figure 3.

B. The Generation-II ERPC Detectors

Recently developed second-generation energy-resolved photon-counting detectors are used to construct this system. Each detector consists of 4 EPRC ASICs with dimensions of $22\text{ mm} \times 11\text{ mm}$. The ERPC ASIC has a total of 2048 readout channels arranged in an array of 32×64 pixels. The pixel pitch size is $0.35\text{ mm} \times 0.35\text{ mm}$ and the intrinsic energy resolution of the ERPC detector is around 3keV at 140keV events. We have previously reported the performance of the first generation ERPC ASICs in [3]. 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 ERPC detector to provide promising imaging performance [4-5].

Figure 4 demonstrates the detector module components. A user designed delicate copper heat sink is used to efficiently disperse the heat generated by ASICs. The ERPC detector is mounted on a rapid prototyping base plate which has air channel embedded as shown below.

C. Aperture Design

A casted lead aperture tube with platinum pinhole inserts have been developed for this stationary SPECT system. With higher stopping power, platinum pinholes are fabricated to minimize the gamma ray penetration through the edge of pinhole inserts. The inner diameter of the lead tube is 6cm and the tube thickness is 16mm. The opposite detectors are placed 15.6cm 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%. Four pinholes of 300 or 500 μm diameter are used for each detector and all pinholes are inserted in the cylindrical lead aperture tube as a ring shown in figure 5. The pinhole open angle is 50 degree and the height is 6mm. As shown in the figure 5, 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. Figure 6 is designed example projection margins on two adjacent detectors.

To calculate precise system response function, we have previously developed a mathematical model to mimic the pinhole aperture as multiple layers of thin sheets [5]. We can also use aperture tube with a smaller inner diameter (larger magnification) to obtain a further improved imaging resolution. The current aperture design allows us to insert a birdcage RF coil inside the aperture for simultaneous SPECT/MR imaging.

D. Modeling of System Response Function and Image Reconstruction

We have previously developed an accurate geometry calibration routine to obtain system response function outside the magnetic field [5]. To precisely derive the system response

function inside the pre-existed MR scanner, a comprehensive charge collection model inside strong magnetic field is developed [4]. In this model, when an interaction happens, the movement of each charge carrier can be tracked and the trajectory can be recorded. This model can accurately predict the detector's energy and spatial response to gamma ray incident events and then help to compensate for the event position recording error due to electron shifting in the strong magnetic field. Specifically, this model will allow us to derive the response of the ERPC detector for interactions occurred at any given locations inside the detector, which will be used in the reconstruction to get high resolution SPECT images. Previous study has already shown obvious improvement by applying this model to SPECT image reconstruction process. The Ordered Subset Expectation Maximization (OSEM) algorithm will be used to reconstruct the image.

III. RESULTS

A. The MRC-SPECT System

The figure 7 is the assembled MR compatible SPECT system. It can be seen that ten detectors are closely packing around the system housing. The system is sitting on a low profile support to work as a bench top ultrahigh resolution SPECT system. This compact system can also be conveniently used inside a MR scanner to perform dual modality imaging study. Figure 8 shows the system working inside a Siemens MR scanner. The system housing outer diameter is 248mm and the MR bore diameter is 350mm.

B. Preliminary Imaging Performance

We have carried out several imaging studies based on a point source phantom to evaluate the imaging performance of this system,. In this study, a Co-57 point source is controlled by precise linear motors (Newport MFA-CC) to generate a regular-triangular shape phantom. The diameter of the point source is 250 μ m and its activity is around 70 μ Ci. The distance between the neighboring point source can be adjusted by choosing different motor movement step size as shown in figure 9. The 300 μ m pinholes are used in this imaging study.

It can be clearly seen that the 500 μ m features can be easily resolved. The 350 μ m features are also well-separated. While this imaging study was carried outside the MR field, we have previously investigated the imaging performance of a prototype rotational MRC-SPECT system inside MR scanner [4] 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.

IV. CONCLUSIONS AND DISCUSSIONS

In this paper, a stationary MR compatible SPECT system is constructed. It is based on up to twenty generation-II energy-resolved photon-counting detectors. Each detector is associated with four pinholes. A 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 μ m spatial resolution. Preliminary

experimental results 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 to further investigate the performance of this ultrahigh resolution MR compatible SPECT system.

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Fig. 1.
The MRC-SPECT system drawing

Fig. 2.
System rear cover and 12 channel electronics PCB board

Fig. 3.
Two 10-detector rings can be put together to deliver a 20-detector system

Fig. 4. Gen-II ERPC detector: the detector module assemble drawing (up) and the real detector module (down)

Fig. 5.
The designed aperture and its cross section, pinholes are buried under the slots as shown above

Fig. 6. The designed projections in two adjacent detectors, round dash lines represent projection margins of a 20mm diameter spherical object

Fig. 7.
The assembled MR compatible SPECT system(up) and its front/back view

Fig. 8.
The MRC-SPECT system inside a Siemens MR scanner

Fig. 9.
The preliminary point source phantom study