Artificial Compound-Eye Gamma Camera for MRI Compatible SPECT Imaging

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Abstract—In this work, we proposed a next generation MRI compatible SPECT system, MRC-SPECT-II, based on an artificial compound eye (ACE) gamma camera design inspired by compound eyes often found in small invertebrate. The MRC-SPECT II had a very compact—6cm detector ring size, but it consisted of 1536 independent micro-pinhole-gamma-camera-elements looking at the object. Each of the micro-camera-elements covered a narrow view angular in the object space. This system design could cover a FOV of 1cm diameter with a very rich angular sampling. Furthermore, the Monte Carlo study showed MRC-SPECT-II could achieve peak geometry efficiency of around 1.5% (as compared to the typical levels of 0.1%-0.01% found in modern pre-clinical SPECT instruments), while maintaining a spatial resolution of around 0.5 mm. Compared to the MRC-SPECT-I system that we have developed, the compact MRC-SPECT-II system could sit inside pre-clinical MRI scanner and potentially allowed us to take MRI and SPECT imaging at the same time. Also the dramatic increase in sensitivity could potentially lead to a radical change in how we might employ SPECT imaging in both pre-clinical and (potentially) clinical practice, by offering much lower detection limit and allowing for new imaging procedures that would be difficult to implement with the current generation of SPECT instrumentations.

I. INTRODUCTION

Dual-modality imaging systems such as PET/CT and SPECT/CT, could provide anatomical and functional information at the same time, which have found a wide array of applications in the pre-clinical and clinical imaging. However, compared with MRI, CT does not have a good contrast for soft tissue and induces extra radiation dose. Combining MRI with PET and SPECT shows great potential and is drawn extensive research and commercial effort. The technical challenge for integrating MRI with PET or SPECT is that the two imaging system inference with each other MRI highly uniform magnetic field T1 Field, high-power radiofrequency pulses, as well as rapidly switching gradient magnetic fields may affect and be affected by nuclear imaging systems [1]. MRI/PET has been a made great progress in the last few years [2-9]. Compared with MRI/PET, MRI/SPECT is lagging behind, partially because of two additional challenging issues. First is aperture issue. The bulk structure of this structure would have eddy currents induced by rapidly switching gradient field and potential affect magnetic field of MRI. How to make MRI compatible aperture, while maintain good shielding and collimating is the problem that have to be solve before we fusing both imaging modalities. Another is that conventional rotation SPECT system cannot be implemented within high magnetic field without inducing artifacts of MRI imaging [1], and therefore stationary design have to be used. Several groups have spent intensive research effort solving those issues. In 2013, Karel Deprez et al. constructed MRI compatible aperture using rapid additive manufacturing with selective laser melting of tungsten powder [10]. Wagenaar et al. has reported the design considerations of an MRI compatible SPECT system based on CZT detectors [11]. A prototype of MRI compatible SPECT system developed by the same group has been reported in [12].

Our group has previously developed a prototype MRI compatible SPECT system [13], and then, a fully-stationary MRI compatible SPECT system (MRC-SPECT-I) [14-15] (as shown in Fig. 6). This system consisted of 40 small-pixel CdTe detector modules (10 detectors, each had 4 modules) assembled in a fully ring SPECT geometry, coupling with 40 inserted pinhole aperture. Each module had CdTe detector having an overall size of 2.2 cm × 1.1 cm, divided into 64 × 32 pixels with size of 350μm. The system was installed on a 25cm diameter non-metal gantry constructed with 3-D printing using nylon powder material. This compact system could be placed inside Siemens 3T clinical MRI scanner. The system could achieve geometry sensitivity around 0.04% for 0.45mm diameter pinhole. We have carried out series of experiments demonstrated this system was capable of providing an imaging resolution of <500μm, when operated inside Siemens 3T clinical MR scanners.

Although MRC-SPECT-I is a state of art MRI compatible SPECT system, there are several aspects to be further improved. First, the system has an outer diameter of 25cm, which is still too large to be placed inside many pre-clinical MRI scanners. To take MRI/SPECT imaging, it has to sit on side of pre-clinical MRI scanner. Second, the system has geometry sensitivity around 0.04% with 40 sampling angles, which would be limiting for some functional imaging applications. So dramatically improved system sensitivity would be desired for future generation of the MRC-SPECT system.

To overcome these drawbacks, we have proposed a MR-SPECT-II system design that utilized an artificial compound eye design inspired by the compound eyes typically seen in small invertebrate animals, such as fire ants, bark beetles, bees and dragonflies [16,17]. This unique system design could offer several attractive features. First, with a total of 1536 small-pinhole-camera-elements, looking at the object at the same time, the MRC-SPECT-II system could offer dramatically improved system sensitivity, over MRC-SPECT-I, while maintaining an excellent imaging resolution.
Fig. 2: Design of the dense camera array (DCA) module. Left: Major components of the DCA module. Right: Cross sectional view of the micro pinhole camera elements.

Fig. 1: Design of an ECGC module. A: Major components of the module. B: Cross sectional view of the micro pinhole camera elements.

II. Method and Materials

A. Artificial Compound-Eye Gamma Camera

The proposed artificial compound-eye (ACE) gamma camera detector module was shown in Fig. 3. It consisted of an ultrahigh resolution gamma ray detector coupled to a special aperture that essentially defined an $8 \times 8$ array of closely packed micro-pinhole-camera-elements (MPCEs). Each MPCE had a pinhole with its shape chosen to confine the projection of the object through the pinhole to be projected onto a small and non-overlapping sub-area on the detector. The physical shape of each pinhole opening could only allow for a small angular coverage of several degrees only. Detector units belonged to each element had area of 3.2 mm in width. To ensure each micro-camera-element to have a sufficient resolving power, the gamma ray detector used behind the collimator needed to have an ultrahigh intrinsic resolution, ideally below 100 $\mu$m. i.e., each element had $>32 \times 32$ high resolution detecting units.

With the basic ACE camera concept, the shape of each pinhole could be designed to allow certain degree of projection overlapping, which could help to further improve the angular coverage of each MPCE, but at the same reduced the information content per detected photon. As the ACE camera design offered enormous amount of freedom in fine-tuning the aperture design, we would like to leave the aperture optimization problem to our future studies. Here we would focus on the non-overlapping aperture design, and demonstrate the performance benefit of the ACE camera for SPECT imaging applications.
Fig. 3: A: 3d Configuration of MRC-SPECT II  B: Sagittal cross section of MRC-SPECT II: 24 rings along the axis direction; each ring has elements and total 1446 micro-pinhole camera elements; each micro camera element has 3.2mmx3.2mm detection area and it focuses to spherical FOV with diameter 1cm and only cover part of it.

Fig 4: Transverse cross view of MRC-SPECT II (middle):
1) Total 24 rings, each ring with 64 micro-pinhole cameras.
2) Four rings are shown and specified by using different color (cyan, green, blue and magenta, sorry for using back and white printing guys,^.^).
3) c is FOV with diameter 1cm, d is object with diameter 2cm.
4) a1, a2, b1 and b2 are micro-pinhole camera elements; they consist of 3.2mm x 3.2mm detection unit and a collimator. a1 and a2 are in the same ring while b1 and b2 are in the adjacent ring to the one where a1 and a2 sit.
5) To demonstrate the angular sampling in FOV, 10 lines are drawn in side each pinhole open area. They are uniformly distributed and across the object; 5)
1, 2, 3 and 4 are sampling point from FOV center to boundary of object. Their distance to FOV center are 0mm, 5mm, 7.5mm and 10mm respectively. Subplot 1, 2, 3 and 4 are corresponding zooming in plot showing that the lines cross 1mm x 1mm area around the sampling points.
B. MRC-SPECT II System and Aperture Design

The schematic of MRC-SPECT-II system was shown in Fig. 3 and Fig.4. It had 8 ACE camera modules and 24 detector rings. Each ACE detector module consisted of 2.56 × 2.56 cm². Each ring had 64 micro-camera-elements (MPCEs) and total 1536 elements in the whole system.

Since each MPCE only covered small opening angle (Fig.2) and part of FOV (Fig.3), how to design the distribution of MPCEs and their orientation was essential issue to have the desired FOV and optimized the angular sampling. In the current design of the MRC-SPECT-II system, there were total of 24 rings of MPCEs along the axis of the system. These 24 rings focused onto the designated FOV area, as shown in Fig.3 B. Inside each ring as shown in Fig.4, MPCEs did NOT focus central of FOV. Its orientation was determined by the position of its 32×32 detector units and pinhole. The pinhole position was the intersection point between the aperture center plane and tangent line of FOV circle, which was drawn from one end of detector units, belonged to the corresponding MPCE. In the even order ring, the tangent line was draw from the first end (the one with smaller azimuthal angle). In the odd order ring, the tangent line was drawn from the other end of the detector units. For example, as shown in Fig. 4, the element a1 and a2 were in the same odd ring. Their pinhole positions were the intersection point of aperture center plane with the FOV circle tangent lines from the left end (smaller azimuthal angle) of their detection units, while b1 and b2 were in the even ring and the tangent lines were from the right end. To further improve the angular sampling, the rings were twisted.

In order to demonstrate the angular sampling, the resultant angular sampling using adjacent 4 rings were demonstrated in the Fig. 4. We further chose four small regions (each is 1 mm ×1mm in size) located from the center to the edge of the FOV (0mm, 5mm, 7.5mm and 10mm respectively), and plotted the angular sampling lines crossing each of these points, which allowed us to compare the spatially-different angular sampling density at difference locations in the object.

C. MRC-SPECT-I system

Since the main propose of this study was to demonstrate that the use of the ACE camera design could lead to a dramatically improved imaging performance, we specifically compared the MRC-SPECT-II system against MRC-SPECT-I system, as shown in Fig. 7. MRC-SPECT-I system consisted of ten ERPC detectors, which had 4 asic modules, assembled as a compact ring. The distance between the opposite detectors was 15.6 cm and the detection area of each detector was 22.5 ×45 mm². Each detector had four 300 to 500 µm pinholes and the object to pinhole distance was designed to be around 36 mm. Note that the modeling of MRC-SPECT-I system was fully validated with our experimental assessment of the actual MRC-SPECT-I system.

D. Monte Carlo Simulation and Reconstruction

A Monte Carlo simulation study based on the system configuration shown in Fig. 3 was carried on. In this study, the system response matrix was pre calculated using analytical model, incorporating a comprehensive system model that includes the effect of DOI, and the photon penetration through the complex pinhole geometry using the SPECT simulation package that we had previously developed. We simulated the use of CZT detector of 2 mm thickness. It provided a stopping power of around 68% for 140keV gamma rays normally incident on the detector. Hot rod cylinder resolution phantom in Fig. 5.a was used. The phantom was assumed to present different kind of activity (1mCi, 0.1mCi and 0.01mCi) and 30mins acquisition time and passion noise was added. And the other parameters were shown in Table I. Image reconstruction was based on the regular maximum-likelihood (ML) algorithms.

E. FOV study

A grid phantom shown in Fig. 5.b was used to study FOV of MRC-SPECT-II system. The grid point was a sphere with diameter of 0.75mm and the distance between grid points was 1.5mm. There was ten grid points in each dimension and the size of phantom was around 15mm. The noiseless data was used to reconstruct the phantom.

III. RESULTS

A. System Size

The whole system had 24 detector rings and 1536 micro-pinhole camera elements. The whole system was very SPECT-II compact. As shown in Fig.6.C, the detector ring size of
MRC-SPECT-I was about 6cm, which was less than half of size of MRC-SPECT-I. It was possible that the whole system could be placed inside small animal MRI scanner (around 10cm) and simultaneous SPECT and MRI imaging could be achieved.

B. Angular sampling

The angular sampling of sample points in fig.4 was shown in sub plot of Fig.4 and more detail related to sampling distribution could be found in Fig.8. From Fig.4 and Fig.8, we could find inside FOV (point 1 and point 2 in Fig.4) could be uniformly sample in 360°. The points 1 could be seen by all 64 micro-pinhole camera in each ring. And the total numbers of sampling angles were 256 in the adjacent 4 twisted rings. Points at the boundary of FOV, like point 2 in Fig.4, could be seen by half pinhole camera elements and totally 128 uniform distributed elements in the adjacent 4 twisted ring could see them. Outside the FOV, like points 3 and 4 in Fig.4, the angular sample was limited and only the micro-pinhole camera elements in the region, which was closest and furthest to them, could see those points.

C. System sensitivity

The geometry sensitivity profile for 0.3mm diameter pinhole MRC-SPECT II system was shown in Fig.9. The peak sensitivity could reach around 1.5% in the central FOV and any points in central transverse slice could have sensitivity larger than 0.6%. The sensitivity around the axis reduced as the position away from the center FOV.

D. FOV study

The reconstructed image of grid phantom in fig.5.b for FOV study was shown in Fig. 10. We could find that the grid points inside the 1cm FOV could be resolved, while the point outside the FOV were distorted due to the limited angular sampling.

E. Resolution Phantom Image

The Monte Carlo simulation results were shown in Fig. 10. In Fig 10, from left to right, were reconstructed image for acquisition 30mins and radioactivity of 1mci, 100micro ci and 10 micro ci respectively. For 1mci scenario, we could find both systems had similar resolution—0.45mm~0.55mm. With decreasing of radioactivity, the noise affected image quality. The advantage of high sensitivity and abundant angular sampling in MRC-SPECT II showed up. We could find this from image of 100micro-ci and 10micro-ci. The images of MRC-SPECT-II had temporally resolution around 0.55mm and 0.65mm respectively, while temporal resolution of MRC-SPECT-I became much more blurring due to noise effects.

IV. CONCLUSIONS

In this work, a highly compact MRI SPECT system, MRC-SPECT II, was proposed based artificial compound eye camera. Monte Carlo simulation demonstrated that this system could achieve 1.5% peak geometry sensitivity while the system resolution could achieve sub millimeter and have FOV of 1cm.
Due to its compact geometry, this system could be placed inside pre-clinical MRI and potential take simultaneous MRI/SPECT imaging. And due to its high sensitivity and rich angular sampling, the imaging quality has a tremendous improvement from our current MRC-SPECT-I system.

There are still several concerns for developing this system. First is the detector issue. We proposed to use 0.1mm pixel size CdTe detector, which was smaller than the size of charge clouds generating by 140keV photons. The charge collection efficiency will be very poor and will affect event collection efficiency. Also the system had high focusing geometry along axis and photon incident angle to detector space will be very large, in some area nearly 50\degree. And to improve detection efficiency, 2mm thickness detector was proposed to use. Large incident angle and 2mm thickness detector will induce two problems: On is the parallax error. Without DOI information, the detector only has 2mm resolution along detector vertical direction, while the other two dimensions have 0.1mm resolution. And the other one is the overlapping issue. Without DIO information, the overlapping area is much larger than it should be. Then the information each event carry will reduce. To solve those problems, a new 100 \mu m pixel CdTe detector with a hybrid pixel-waveform (HPWF) readout system is under development. This detector consisted of a CMOS photon-counting ASIC (256 pixel x 256 pixel) in the anode to handle the small pixels, and a waveform sampling circuitry to sample the signal waveform induced on the cathode by electron and hole movement inside the CdTe detector bulk. This approach is designed to overcome the poor charge collection efficiency and provides DOI information of detected events.

Another issue is related to aperture fabrication and modeling. The aperture has 1536 pinholes and those holes have different shape and orientation. The conventional fabrication methods nearly impossibly construct such a complicated structure. Rapid additive manufacturing with selective laser melting [10] potentially solves this issue. Also the complicated aperture leads to a challenging task for system
modeling. Ray tracing method to derive response function is hard to achieve enough accuracy due to the discrepancy between the actual fabricated and designed geometry, difficulty in calibrating system parameters, like pinhole position and orientation, and the effect of small open angle. It seems system modeling based on experiment data could potentially solve this issue.

V. REFERENCES


