Characterization of Cross-compatibility of Small Animal Insertable PET and MRI

Jihoon Kang, Yong Choi, Member, IEEE, Key Jo Hong, Jin Ho Jung, Wei Hu, Geun Ho Lim, Byung Jun Min, Seung Han Shin, Yoon Suk Huh and Hyun Keong Lim

Abstract—The purpose of this study is cross-compatibility of PET and MRI was characterized to explore the optimal method overcoming possible interferences between them. MR phantom images were acquired by placing the PET components inside and outside RF-coil in 7-T MRI to examine the effect of the relative position of PET detector and RF-coil on MRI. Theoretical evaluation of shielding effectiveness (SE) of plate and mesh Cu shielding were calculated to characterize criteria for reducing mutual interference between PET and MRI. Experimental studies were performed that MR image quality as a function of the area and thickness of Cu plate was examined to characterize the effect of plate shielding method. Also, MR images as a function of the open area of Cu mesh were acquired. Moreover, it was proposed and evaluated to minimize the cross-interference that only crystal and photo-sensor are placed inside MRI bore and the PET signals were transmitted to the signal amplifier circuits using long cable for developing hybrid PET-MR imaging system. Significant artifacts were generated on MRI by inserting the PET module inside RF-coil, but obvious degradation of the MR image quality was not observed by placing the PET module outside RF-coil. In theoretical evaluation, Cu plate shielding need to be thicker than 15–30 µm and Cu mesh shielding need to be thicker than 0.7/1.5/5.5-mm for minimizing the mutual interference between PET and MRI when the hole sizes of mesh were 0.5/1/3-mm, respectively. Cu thickness did not affect the homogeneity but SNR of MR images changed from 150 to 110 when Cu thickness changed from 0 to 200 µm. The SNR and homogeneity were considerably changed from 270 to 29 and from 88 to 69 when 160 and 640 cm2 Cu area were employed. The temperature of Cu was risen by ~1°C when large area shielding (640 cm2) was used. MR image quality was not improved by increasing open area in GRE sequence. Moreover, this study verified charge signal transmission method using long cable, and it was feasible to acquire artifacts-free PET-MR images without any shielding material by placing the amplifier outside MR bore. In summary, cross-interferences between two imaging modalities would be minimized by placing the PET module outside RF-coil and inside gradient coil of MRI. In Cu plate shielding, area is a potentially bigger risk factor than the thickness in deteriorating MRI SNR, homogeneity and stable temperature operation. Cu mesh shielding with <4% open area will maximize the cross-compatibility of PET and MRI. Charge signal transmission using long cable between PET detector and preamplifier allows maximizing the cross-compatibility of PET and MRI and this approach is preferable because it allows locating only PET detector inside MRI without any shielding material.

I. INTRODUCTION

There has been great interest in the development of hybrid PET-MR imaging system which provides many advantages comparing with PET-CT [1][2]. An insertable animal PET based on GAPD has been developed to obtain simultaneous PET-MR images in our lab (Fig 1-3). It is important to minimize the mutual interferences between PET and MRI to acquire high quality simultaneous images from both modalities [3][4].

Fig. 1 Animal PET insertable to MRI based on GAPD

Fig. 2 Reconstructed PET images of hot (left) and cold-phantoms (right) acquired to evaluate performance of the proof-of-principle PET.

Fig. 3 Tumor mouse (left) and FDG PET images (right) obtained at different bed position.
The goal of this study is to propose a designing scheme of the hybrid animal PET-MRI that allows to simultaneously obtaining high quality PET and MR images. The cross-compatibility of PET and MRI was characterized to explore the optimal method overcoming possible interferences between them. The following conditions were investigated:
- Effect of the relative position of PET detector and RF-coil on MRI
- Effect of area and thickness of Cu plate shielding of PET components on MRI
- Effect of apertures of Cu mesh shielding of PET components on MRI
- Effect of charge signal transmission method using long cable on MRI and PET

II. MATERIALS AND METHODS

A. Small Animal Insertable PET and 7-T MRI

1) Small animal PET insertable to MRI

Full-ring PET scanner consisted of 16 detector modules arranged in a ring with an inner diameter of 70 mm. Each PET detector consisted of a 13 x 13-mm LYSO array (Sinocera, Shanghai, China) that contained 4 x 4 individual 3 x 3 x 10-mm crystals arranged with a pitch of 3.3 mm. The crystal elements were polished and separated with white epoxy except for an entrance face. The 3-side buttable GAPD, that is possible to integrate the PET ring system without dead space, was used to readout scintillation light. The GAPD 4 x 4 arrays (SensL, Cork, Ireland) consisted of 3 x 3-mm each pixel having 3,640 micro-cells and arranged with a pitch of 3.3 mm. Individual crystal coupled one to one with a separate pixel of the GAPD. Optical grease was not employed to avoid the crosstalk between the pixels by light distribution in this study. GAPD output signals were fed in to the 16 channel charge sensitive preamplifiers and it was fabricated with non-magnetic components.

2) Small animal 7-T MRI

Experiment was performed with a 7-T animal MRI (Bruker BioSpin MRI, Ettlingen, Germany) to characterize the cross-compatibility. MR images were acquired with the insertable PET located at the MR iso-center. MR images of a CuSO4-filled phantom (10 mm outer diameter, 50 mm length) were acquired using three MR image sequences such as Gradient Echo image (TR=205 ms, TE=6 ms, FA=15°), Spin Echo T1 weighted image (TR=420 ms, TE=8 ms) and Spin Echo T2 weighted image (TR=3,000 ms, TE=75 ms) sequence. MR image was analyzed following the guidelines of the American Association of Physicists in Medicine (AAPM) [5].

B. Effect of the relative position of PET detector and RF-coil on MRI

There are two possible configurations for designing a hybrid PET-MR imaging system that one places the PET detector inside RF-coil and the other places it outside RF-coil. MR phantom images were acquired by placing the PET components inside and outside RF-coil in 7-T MRI to examine the effect of the relative position of PET detector and RF-coil on MRI.

C. Theoretical evaluation of SE of Cu shielding to characterize criteria for reducing mutual interference between PET and MRI

1) Thickness criteria of Cu plate used to shield cross-compatibility of PET and MRI

Shielding effectiveness (SE) of Cu plate was calculated to characterize criteria for reducing mutual interference between PET and MRI. SE is consisted of three terms in magnetic near-field condition [6][7]. The reflection loss (R) is attenuation due to the reflection of power at the interfaces and an absorption loss (A) is attenuation due to power converted to heat as the wave propagates through the material. Also, correction factor (B) is reduced SE if A < 10 dB. In our study, calculation conditions of near-field SE were that distance from EM source to Cu shield was 2 cm (considering the scheme of our hybrid PET-MR) and purity of Cu shielding material was more than 99%.

\[
SE_{\text{plan}}(dB) = R + A + B
= 20 \log \left( \frac{\eta}{4 \eta_s} \right) + 20 \log e^{\frac{t}{\delta}} + 20 \log e^{\frac{t}{\delta}}
\]

thickness of Cu shielding : \( t \)

Intrinsic impedance of free space : \( \eta = \sqrt{\mu / \varepsilon_s} = 377 \, \Omega \)

Intrinsic impedance of Cu : \( \eta_s = \sqrt{\frac{2 \pi f \mu_s}{\sigma}} = 6.44 \times 10^4 \, \Omega \)

Skin depth of Cu : \( \delta = \sqrt{\frac{1}{2 \pi f \mu_s \sigma}} \)

Frequency of EM source : \( f = 300 \, MHz \)

Magnetic permeability : \( \mu_s = \mu = 4 \pi \times 10^{-7} \, H / m \)

Electrical conductivity : \( \sigma = 5.7 \times 10^7 \, S / m \)

2) Apertures criteria of Cu mesh to shield cross-compatibility of PET and MRI

Mesh designed shielding is expected to improve the MR image quality because of the reduction of conductive material amount in MRI bore. However, SE would be degraded due to

<table>
<thead>
<tr>
<th>Effect of MRI on PET</th>
<th>Effect of PET on MRI</th>
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<tbody>
<tr>
<td>- malfunction of PET electronic signals by the PET detector and circuit boards</td>
<td>- heat generation by eddy currents induced from the gradient field</td>
</tr>
<tr>
<td>- gradient field caused by high magnetic field, RF field</td>
<td>- heat generation by eddy currents induced from the gradient field</td>
</tr>
<tr>
<td>- malfunction of PET electronics</td>
<td>- distortion of MR images by the PET shielding and circuit boards</td>
</tr>
</tbody>
</table>

Table I. The cross-interference between PET and MRI
the presence of holes. The influence of the size and number of apertures was evaluated to characterize the effect of using Cu mesh shielding. SE of PET housing with multiple circular apertures can be expressed as [8][9]

\[
SE_{\text{max}} (dB) = 20\log \frac{\lambda}{2d} - 10\log n + 32 \frac{t}{d}
\]

\(\lambda\) : wavelength of EM source  
\(d\) : diameter of circular hole  
\(n\) : number of apertures within a distance of \(\lambda/2\)  
\(t\) : thickness of Cu mesh

D. Effect of area and thickness of Cu plate shielding on MRI

MR image quality as a function of the area and thickness of Cu plate was examined to characterize the effect of plate shielding method on MRI. Thickness of Cu plate with 160 cm² area was varied from 0 to 200 μm and Area of Cu plate with 50 μm thickness was varied from 160 to 640 cm². Temperature probe was placed on the PET components to measure heat generation inside the Cu shielding by eddy current.

E. Effect of open area of Cu mesh shielding on MRI

MR images as a function of the open area of Cu mesh were acquired. The hole size was changed from 0 to 10 mm. In this study, the number of holes and thickness of Cu mesh were 10 and 100 μm, respectively.

F. Effect of charge signal transmission method using long cable on MRI and PET

In the previously reported hybrid PET-MR imaging systems based on semiconductor photo-sensor, the problem of a possible mutual interaction is still presented by positioning the conductive material such as preamplifier and shielding material in MRI bore (Fig. 4) [10]. Fig. 5 shows the proposed concept for developing hybrid PET-MR imaging system that the only crystal and photo-sensor are placed inside MRI bore and the PET signals were transmitted to the signal amplifier circuits using long cable. The proposed method allows designing MR compatible PET detector without Cu shielding material for protecting the amplifier circuits. MR images and PET data were simultaneously acquired using PET detector module and 7-T MRI. Only LYSO, GAPD and signal transmission cable was inserted inside MRI bore while the amplifier circuits were located outside MRI bore.

III. RESULTS

A. Effect of the relative position of PET detector and RF-coil on MRI

Significant artifacts were generated on MRI by inserting the PET module inside RF coil (Fig 6.a) and the incompatibilities resulted from close distance between MR phantom and PET components. No obvious degradation of the MR image quality was observed by placing the PET module outside RF-coil (Fig 6.b).

<table>
<thead>
<tr>
<th>MR image</th>
<th>No PET</th>
<th>LYSO+GAPD</th>
<th>Preamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>42.5</td>
<td>8.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Homogeneity</td>
<td>94.2</td>
<td>52.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

(a) effect of inserted PET inside RF-coil of MR image

<table>
<thead>
<tr>
<th>MR image</th>
<th>No PET</th>
<th>PET module</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>143.8</td>
<td>143.1</td>
</tr>
<tr>
<td>Homogeneity</td>
<td>97.6</td>
<td>97.2</td>
</tr>
</tbody>
</table>

(b) effect of inserted PET outside RF-coil of MR image

Fig. 6 Effect of the relative position of PET detector and RF-coil on MR image

B. Theoretical evaluation of SE of Cu shielding to characterize criteria for reducing mutual interference between PET and MRI

1) Thickness criteria of Cu plate used to shield cross-compatibility of PET and MRI
Absorption loss was linearly increased as a function of Cu plate thickness, while reflection loss was remained constant. The criteria of SE of Cu plate shielding were evaluated theoretically. For minimizing the effect of RF field (300 MHz) on PET, it is not important to consider the thickness of Cu plate shielding, since minimum SE of Cu shielding was expected more than 60 dB (99.9%). However, for minimizing the effect of PET electronics (100 MHz) on MR, the thickness of Cu plate shielding need to thicker than 15 ~30 μm, since American Association of Physicists in Medicine (AAPM) Nuclear Magnetic Resonance (NMR) Committee have been recommended that RF shielding should provide a minimum attenuation level of 80 ~ 100 dB (99.99 ~ 99.999%) for MRI operation [11][12].

2) Apertures criteria of Cu mesh to shield cross-compatibility of PET and MRI

SE was dominantly dependent upon the dimension rather than the number of the aperture. Fig. 8 shows the SE for various aperture sizes in Cu mesh with 10 holes. For reducing effect of RF field on PET, Cu mesh shielding need to thicker than 0.2/0.5/ 2.5-mm for providing an attenuation level of 60 dB when the hole sizes of mesh were 0.5/ 1/ 3-mm, respectively. For reducing effect of PET electronics on MRI, Cu mesh shielding need to thicker than 0.7/1.5/ 5.5-mm for providing an attenuation level of 100 dB when the hole sizes of mesh were 0.5/ 1/ 3-mm, respectively. It is difficult to predict that the Cu mesh with large hole size (>1 mm) would improve the cross-interference, since they need increasing Cu thickness more than 500 times comparing with 30 μm plate shielding.

(a) Effect of RF field (300 MHz) on PET

(b) Effect of PET electronics (100 MHz) on MR

C. Effect of area and thickness of Cu plate shielding on MRI

1) Effect of area of Cu plate shielding on MR image

Fig. 9 demonstrates that area of Cu plated shielding plays an important role on the SNR and homogeneity of MRI. The temperature of shielding material was risen ~ 0.7°C caused by eddy current generation when larger area (640 cm²) shielding was introduced. The heat generation could be a potential risk factor deteriorating the performance of PET scanner based on semiconductor photo-sensor.

2) Effect of thickness of Cu plate shielding on MR image

Fig.10 demonstrates the effect on MR image as a function of thickness of Cu shielding. The thickness of Cu plate shielding did not affect the homogeneity of MR images and the
temperature of shielding material. However, the SNR of MR images were gradually degraded as an increase of the thickness.

D. Effect of open area of Cu mesh shielding on MRI

MR image quality represented by homogeneity and SNR was not improved by increasing open area in GRE sequence (Fig 11.a). SNR of MR images was linearly increased and the saturated at 4% open area in SE-T1 sequence (Fig 11.b). The results suggest that the cross-compatibility is maximized by introducing Cu mesh shielding with 4% open area.

E. Effect of charge signal transmission method using long cable on MRI and PET

No obvious artifact or change of line profiles were observed in MR images (Fig. 12). PET performance was not significantly changed while running the MRI sequences (Fig. 13). The problem of a possible mutual interaction was minimized by inserting only LYSO and GAPD without any RF shielding materials or electronic circuits inside MRI bore. Our results demonstrated that it is possible to operate the hybrid PET-MR imaging system without any shielding material by placing the amplifier outside MR bore.

IV. SUMMARY AND CONCLUSION

Cross-interferences between two imaging modalities of hybrid PET-MR imaging system would be minimized by placing the PET module outside RF-coil and inside gradient coil of MRI. Theoretical evaluation suggests that thickness criteria of the Cu plate shielding for providing 99.999% attenuation level is 30 μm. Cu mesh shielding should have small size and number for minimizing effect of MR on PET.

Thin and segmented plate shielding is preferable over thick and large area Cu plate shielding to reduce the effect of PET on MRI. In Cu plate shielding, area is potentially bigger risk...
factor than thickness in deteriorating MRI SNR, homogeneity and stable temperature operation. Cu mesh shielding with < 4% open area will maximize the cross-compatibility of PET and MRI. Charge signal transmission using long cable between PET detector and preamplifier allows maximizing the cross-compatibility of PET and MRI. This approach is preferable because it allows locating only PET detector inside MRI without any shielding material.

REFERENCES


