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NOTE

MR image corrections for PET-induced gradient distortions

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Abstract

The combination of positron emission tomography (PET) and magnetic resonance imaging (MRI) by using PET inserts in existing MRI scanners is an attractive approach. When designing the PET insert, mutual influences of both imaging modalities need to be minimized. The gradient magnetic fields induce eddy currents in all conductive components of the PET insert. Eddy currents produce superimposing magnetic fields distorting the gradient magnetic field. However, the gradient magnetic fields determine how the MRI data is acquired in the k-space. A distorted gradient shape produces a distorted k-space trajectory which then results in a distorted image.

The dynamic performance of the gradient system can be characterized by measuring its gradient impulse response function (GIRF). Knowledge of the GIRF enables to correct the k-space trajectory and thereby enables to reduce image distortions.

We characterized the influence of a preclinical PET insert, i.e. the Hyperion IID, on the gradient performance of a 3 T MRI scanner. The GIRFs up to the second order spherical harmonics were determined with and without the PET insert by measuring frequency-swept gradient pulses with an NMR probe. We calculated a corrected k-space trajectory of a single-shot spiral sequence using the measured GIRFs.

The low-pass characteristic of the gradient system only slightly increased in the presence of the PET insert. We showed a minor influence of the PET insert on the GIRFs, demonstrating the high gradient transparency of the PET insert. The single-shot spiral image measured in the presence of the PET insert and reconstructed with the uncorrected k-space trajectory was blurred and distorted. We strongly reduced the blurring and distortion by using the corrected k-space trajectory predicted with the measured GIRFs up to the first order spherical harmonics. Slight blurring remained in the corrected image caused by either second order spherical harmonics or distortions of the static magnetic field.

1. Introduction

Positron emission tomography (PET) and magnetic resonance imaging (MRI) can be combined by placing a PET insert in a clinical MRI scanner. When designing the PET insert, mutual influences of both imaging modalities need to be minimized. A PET insert typically comprises many conductive elements, e.g. cooling pipes, heat spreaders, radio-frequency (RF) shieldings and PCBs with conductive planes. MRI uses switching magnetic fields such as the gradient magnetic fields that induce eddy currents in all conductive elements of the PET insert. The strength and decay time of the eddy currents depend on the conductivity and area of the elements perpendicular to the changing field. The induced eddy currents produce again superimposing magnetic fields, resulting in a distorted gradient magnetic field. However, the gradient magnetic fields determine how the MRI data is acquired in the k-space. A k-space trajectory is calculated by the time integral of the gradient shapes of a given sequence. Thus, a distorted gradient shape produces a distorted k-space trajectory and hence a distorted
The chirp gradient was separately applied in gradient was swept from high to low frequencies to improve the signal-to-noise ratio at the high frequencies. The duration was set to 25 ms. The amplitude was scaled down at higher frequencies because of the slew rate limitation of the PET insert can distort the static magnetic field, radio-frequency field or increase the noise level, all degrading the image quality.

Figure 1(a) (Weissler et al. 2012, Vannesjo et al. 2009, or modified gradient echo (Addy et al. 2012, Vannesjo et al. 2013, 2014). An impulse response function completely describes a linear and time-invariant (LTI) system. The Fourier transform (FT) of the output O of an LTI system is calculated by multiplying the FT of the input I by the FT of the impulse response H:

\[ O(f) = I(f) \cdot H(f). \]

The FT of the impulse response is determined by measuring the output of the system for a known input. The gradient distortion of a PET insert can be described as an LTI system if the insert is always placed at the same position in the MRI. The GIRF comprises the complete information about the time and frequency response of any gradient pulse. Furthermore, the measured GIRF allows to predict the output for an arbitrary input as given by the gradient shapes of an actual sequence. Hence, the GIRF enables to correct a k-space trajectory for image reconstruction (Addy et al. 2012, Vannesjo et al. 2016).

The GIRF can be measured, for example, by a nuclear magnetic resonance (NMR) probe (Doty et al. 1998, De Zanche et al. 2008, Gross-Weege et al. 2018). An NMR probe is basically a water droplet surrounded by a receive or transmit/receive coil (Barmet et al. 2008). The frequency of the NMR signal is proportional to the magnetic field at the location of the water droplet. Thus, the NMR probe allows to measure magnetic fields in a time-resolved manner with high sensitivity and at a precise location without the need for any spatial encoding.

In this work, we use an NMR probe to measure the GIRF of the Hyperion IIP PET insert (Weissler et al. 2015), which is designed for simultaneous acquisition of PET and MRI. Furthermore, we correct the k-space trajectory of a single-shot spiral sequence based on the measured GIRF to minimize gradient induced image distortions.

2. Materials and methods

2.1. Hyperion IIP PET insert

An image of the Hyperion IIP PET insert is depicted in figure 1(a) (Weissler et al. 2015).

The PET insert was designed for a 3 T MRI scanner (Achieva 3 T, Philips, The Netherlands). It comprises 10 detector modules arranged in a ring with an inner diameter of 105 mm. The PET insert can be equipped with a dedicated 3H transmit/receive coil with an inner diameter of 80 mm. The PET performance (Schug et al. 2015, 2016) and MR compatibility (Wehner et al. 2014, 2015, Weissler et al. 2014) were characterized in previous works. Figure 1(b) shows a single detector module without the PET detectors. Many conductive elements, i.e. RF gaskets, heatspreaders, cooling pipes and PCBs with conductive planes are visible. The RF shield is made from carbon fiber composites to improve the gradient transparency (Düppenbecker et al. 2012, Gross-Weege et al. 2018).

2.2. GIRF measurement

To determine the GIRF over a broad frequency range, we used a chirp gradient as the input (Addy et al. 2012, Vannesjo et al. 2014, Gross-Weege et al. 2018). A chirp gradient is a sinusoidal oscillating gradient with a linearly increasing frequency. We set the frequency range to (0–20) kHz, the maximum strength to 30 mT m\(^{-1}\) and the duration to 25 ms. The amplitude was scaled down at higher frequencies because of the slew rate limitation of the MRI gradient system, which is 200 mT m/ms. Since the signal of the NMR probe decays with T2\(\ast\), the chirp gradient was swept from high to low frequencies to improve the signal-to-noise ratio at the high frequencies. The chirp gradient was separately applied in x-, y- and z-direction and is shown in figure 2.
The chirp gradient was measured with the NMR probe for each orientation at nine positions with and without the PET insert. The NMR probe and its measurement principle has been presented previously (Gross-Weege et al. 2018). The signal of the NMR probe was averaged 50 times and was sampled at a rate of 364.58 kHz using the regular MRI readout electronics. A transverse cross-section of the measurement setup with the PET insert is sketched in figure 3.

The PET modules are colored in grey and the RF coil is colored in red. We measured the chirp gradient on a circle with a radius of 58 mm in three different transverse planes, i.e. \( z \) was equal to \(-5\) cm, 0 cm and 5 cm. Thus, the field distribution was characterized by nine field strength values per time point of the chirp gradient. Spherical harmonics up to the second order, as summarized in table 1, were fitted to the field distribution for each time point (Gruetter and Boesch 1992).

The zeroth order spherical harmonic \( Z_0 \) is a space-independent offset field. The first order spherical harmonics \( X, Y \) and \( Z \) are given by the linear gradient fields in \( x \)-, \( y \)- and \( z \)-direction. The second order spherical harmonics are the parabolic components of the field distribution.

The GIRF \( H_{l,m} \) was calculated by dividing the FT of the measured output \( O_{m} \) by the FT of nominal chirp gradient as the input \( I_l \):

\[
\text{GIRF } l \rightarrow m : \quad H_{l,m}(f) = \frac{O_{m}(f)}{I_l(f)}.
\]  

The nominal chirp gradient is applied in \( x \)-, \( y \)- and \( z \)-direction, therefore, \( l \) is given by the first order spherical harmonic functions \( X, Y \) and \( Z \). The output is given by one of the measured spherical harmonics of the chirp gradient:

\[
l \in \{X, Y, Z\}
\]

\[
m \in \{Z_0, X, Y, Z, Z_2, XZ, YZ, XZ - YZ, XY\}.
\]  

2.3. Image correction

All images were acquired with the PET insert placed at the same position in the MRI as for the GIRF measurements.

A coronal slice was measured with a single-shot spiral sequence, which is very sensitive to distortions of the static magnetic field and the gradient fields. Since the slice was placed in coronal orientation, the
k-space was filled in the \((y,z)\) plane. The parameters of the sequence were a slice thickness of 5 mm, a FOV of \((200 \cdot 200)\) mm\(^2\), a matrix size of \((y,z) = (128, 128)\) and a TE/TR of 1.1/68 ms, resulting in a total scan time of 68 ms.

For comparison, we performed a Cartesian gradient echo sequence. The same geometric parameters as for the spiral sequence were applied. Furthermore, we set the TE/TR to 8.7/500 ms, resulting in a total scan time of 64 s.

As a phantom, we used 8 cylindrical bottles of gelatin mixed with a Gadolinium based contrast agent that were placed into one large bottle of gelatin. The inner diameter of each smaller bottles was equal to 1.5 cm and of the larger bottle was equal to 7 cm. We applied a second order iterative shim for all measurements to homogenize the static magnetic field.

The offset fields \(Z_0\) and gradient shapes of the spiral sequence were predicted for each GIRF up to the first order spherical harmonics by multiplying the FT of the input gradient fields of the spiral sequence with the respective GIRF. For each gradient orientation, the predicted gradient shapes were summed up, i.e. also cross correlations were included:

\[
O_m(f) = \sum_l H_{lm}(f) \cdot I_l(f)
\]

\[
l \in \{X, Y, Z\}
\]

\[
m \in \{Z0, X, Y, Z\}.
\]

The offset fields \(Z_0\) were converted in offset phase factors and multiplied by the input raw data (Jehenson and Syrota 1989). The first order gradient fields were separately integrated over the sequence time to calculate a corrected k-space trajectory. Additionally, we calculated the k-space trajectory of the gradient shapes without...
correction for comparison. All other image reconstruction steps, such as the basic corrections and the Cartesian gridding procedure, were performed identically for all images. The images were reconstructed with the free software gpi (Zwart and Pipe 2015).

3. Results

3.1. GIRF measurement

Figure 4 shows the result of the fit of the first order spherical harmonics exemplarily for the chirp gradient applied in z-direction. The input gradient, i.e. the applied chirp gradient, is also added in black. Furthermore, a zoom in the time range (0.02–0.026) s is depicted. Only at low frequencies, i.e. the end of the chirp gradient, the measured gradient in z-direction matched the input gradient. At high frequencies, the measured gradient strength was weaker than the input gradient strength.

Figure 5 depicts the calculated GIRFs for the gradient applied in z- and y-direction with and without the presence of the PET insert. In figures 5(a) and (b), the first order GIRF Y → Z and Z → Y is shown. At low frequencies, the input gradient shape matched the output, i.e. the GIRF was equal to 1. At higher frequencies the GIRF decreased down to about 0.1 at 20 kHz. Furthermore, the noise on the estimation of the GIRF increased for frequencies higher than 20 kHz. For the measurement with the PET insert, the low pass characteristic slightly increased, in particular at higher frequencies. The effect was similar for the GIRF Y → Y and Z → Z.

In figure 5(c), the first order cross correlation GIRF Y → Z and Z → Y is depicted, representing the measured Z and Y gradient while applying the chirp gradient in y- and z-direction, respectively. An minor effect of the PET insert on the GIRF Y → Z is observable. Applying a gradient with a frequency of about 4 kHz in y-direction results in a gradient in x-direction with 1% of the strength of the gradient y-direction. This will result in a slight rotation of the image for most sequences.

Figure 5(d) shows the GIRFs of the zeroth order Y → Z0 and Z → Z0. The GIRF Y → Z0 was very similar, whereas the GIRF Z → Z0 slightly differed for the measurement with and without the PET insert.

In figure 5(e) the GIRFs of the second order spherical harmonic Z → Z2 and Y → Z2 is depicted. The PET insert has a very slight effect on the GIRF Y → Z2. However, the GIRF Z → Z2 with the PET insert strongly increased up to a maximum at about 6 kHz compared to the GIRF without the PET insert.

3.2. Image correction

Figure 6 shows the field offset values Z0 and the k-space trajectories, which were calculated for the single-shot spiral sequence using the GIRFs. In figure 6(a), the field offsets Z0 are depicted over the sequence time. For the sequence without correction, the offset values equal zero. The offset values corrected by the GIRF without PET oscillate at the frequency of the input gradients of the spiral sequence. The field offset increases with the sequence time, following the input gradient strength. The offset values corrected by the GIRF with PET also oscillate with the same frequency as the input gradients of the spiral sequence; however, for the first 18 ms, the phase is shifted by \( \pi \).

Figure 6(b) shows three trajectories of the single-shot spiral sequence: the trajectory without any correction is colored red, the trajectory corrected by the GIRF measured without the PET insert is colored black and the trajectory corrected by the GIRF measured with the PET insert is colored blue. Figure 6(c) shows a zoom of the same plot. A difference especially between the trajectories without correction and with correction is observable. The image acquired with the gradient echo sequence is depicted in figure 7. The image looks very clear and only minor ringing artifacts are visible, caused by the strong signal variations between the gelatin and the plastic of the bottles. The blue line marks the position used for line profiles that are shown below.

The differently reconstructed images acquired with the single-shot spiral sequence in presence of the PET insert are presented in figures 8(a)–(d). The plots in figures 9(a)–(d) show line profiles through these images at
the position that is marked by the blue line in figure 7. For comparison, the line profile of the gradient echo image is added in all plots.

Figure 8(a) shows the reconstruction without applying any correction, i.e. neither correction of the k-space trajectory nor of the field offset. Thus, the k-space trajectory was directly calculated from the gradient shapes. The image looks very blurred, which is also reflected in the line profile in figure 9(a) by the high intensities in the valleys between the smaller phantom rods. Furthermore, the outer part of the phantom bottle looks smaller than in the gradient echo sequence, which is also visible in the line profile.

We reconstructed figure 8(b) with the k-space trajectory and the phase factors, that were corrected by the GIRFs measured without the PET insert. A clear improvement is observable, however, slight blurring especially in between the phantoms is still present. Furthermore, a slight distortion of the phantoms is visible between the line profiles in figure 9(b).

Figure 8(c) was reconstructed with the uncorrected k-space trajectory, but with the phase correction factors corrected by the zeroth order GIRF which was measured with the PET insert. The image looks very clear, however, the line profile in figure 9(c) shows a similar distortion as the line profile in figure 9(a).

For figure 8(d), the k-space trajectory and the phase factors were corrected by both the zeroth and first order GIRFs measured with the PET insert. The image looks even more clear and a reduced distortion is observable in the line profile in figure 9(d).

4. Discussion

4.1. GIRF measurement

For all GIRFs in figure 5, the noise of the measurements increased at higher frequencies because the amplitude of the chirp gradient was limited by the maximum slew rate. Furthermore, the noise increased strongly for frequencies higher than 20 kHz because the maximum bandwidth of the chirp gradient was 20 kHz. Since the signal of the first order spherical harmonics was much higher, the signal-to-noise ratio of the first order GIRFs was higher compared to the zeroth and second order spherical harmonics.

The decrease of the GIRFs of the first order spherical harmonics at higher frequencies in figures 5(a) and (b) was caused by the low pass characteristic of the gradient system (Vannesjo et al 2014).

Comparing the GIRF measurements of all orders with and without the PET insert, differences were observable in particular at higher frequencies because the rapid field changes induce eddy currents causing the field distortions. Therefore, the low pass characteristic of the first order GIRFs with the PET insert slightly increased at higher frequencies compared to the measurements without the PET insert.

The gradient distortion of the Hyperion 11P PET insert was visualized in a qualitative distortion map by Wehner et al (2015). A first order distortion superposed by a second order distortion was measured along the z-axis.
Figure 5. The GIRFs up to the second order spherical harmonics were measured with and without the PET insert: (a) and (b) first order GIRF $Y \rightarrow Y$ and $Z \rightarrow Z$, (c) first order cross correlation GIRF $Y \rightarrow Z$ and $Z \rightarrow Y$, (d) zeroth order GIRF $Y \rightarrow Z_0$ and $Z \rightarrow Z_0$, (d) second order GIRF $Y \rightarrow Z_2$ and $Z \rightarrow Z_2$.

Figure 6. Field offsets and k-space trajectories were calculated for the single-shot spiral sequence: (a) zeroth order field offset $Z_0$, (b) and (c) first order spherical harmonics $Y$ and $Z$ converted into k-space coordinates whereby (c) shows a zoomed in area of (b).
after applying a $z$-gradient. The GIRF $Z \rightarrow Z$ represents the first order distortion and the GIRF $Z \rightarrow Z^2$ represents a second order parabolic distortion along the $z$-axis. In figures 5(b) and (e) the effect of the PET insert is clearly visible for the first order GIRF $Z \rightarrow Z$ and the second order GIRF $Z \rightarrow Z^2$, respectively. Thus, the current result is consistent with the previous measurements.

4.2. Image correction
The field offset values $Z0$ in figure 6(a) are induced by the time-varying gradient fields of the single-shot spiral sequence and thus, they oscillate with the same frequency of the gradient fields.

The PET insert induces a field offset that is opposed to the field offset without PET insert. Therefore, the amplitude of the oscillating field offset decreases from 0 ms to 18 ms with a $\pi$-shifted phase compared to the field offset without PET insert and increases from 18 ms to the end of the sequence without a phase shift.
The reconstruction of the single-shot spiral image using a corrected k-space trajectory and field offset values enabled a reduction of the distortion and the blurring. Using the correction factors predicted by the GIRFs measured with the PET insert resulted in the clearest image figure 8(d). However, using the GIRFs measured without the PET insert already strongly reduced the distortion and blurring (figure 8(b)), demonstrating the high gradient transparency of the PET insert. The zeroth order phase correction especially reduced the blurring of the image as shown in figure 8(c); however, the distortion of the image still remains. This is reduced by applying also the first order correction in figure 8(d), which results in the clearest and least distorted image.

Thus, the dominant field distortions induced by the Hyperion II° PET insert can be described with spherical harmonics up to the first order. However, slight blurring and distortion remains even in the image figure 8(d) that was corrected with the GIRFs up to the first order. A higher order reconstruction including higher order GIRFs might reduce these distortions even more (Wilm et al 2011). This could be especially interesting for PET/MRI systems with a higher geometrical complexity than the Hyperion II° PET insert. Systems with a field of view very close to the conductive components of the PET insert (Parl et al 2017, Lee et al 2018) or systems with a broken symmetry, such as PET inserts for breast imaging (Ravindranath et al 2009, Weissler et al 2018), would probably induce also higher order field distortions. To also include the information of third order spherical harmonic functions, the chirp gradient needs to be measured at 16 positions.

Furthermore, the remaining smaller image distortions in figure 8(d) might be caused by slightly magnetic components of the Hyperion II° PET insert. The PET insert deteriorates the homogeneity of the static magnetic field by 1 ppm within $z = (0 ± 5)$ cm although applying the second order shim. Since the single-shot spiral sequence is also very sensitive to these distortions of the static magnetic field, they might cause the remaining artifacts.

In general, the correction method is easy to implement and the GIRFs could be stored on the reconstruction computer. It was shown before that a measured GIRF of the gradient system without PET insert is very stable over time, even after three years (Vannesjo et al 2016). For a PET insert, the distortion of the gradient fields is proportional to the eddy currents induced in the conductive materials which is proportional to the change of the gradient fields. Since the conductivity is very stable over time, i.e. time-invariant, the same GIRFs can be used for years if the PET insert is always placed at the same position in the MRI. Furthermore, a GIRF comprising...

Figure 9. The plots (a)-(d) show line profiles created for each single-shot spiral image in figures 8(a)-(d) at the position marked by the blue line in figure 7. Additionally, the line profile of the gradient echo image in figure 7 is added in all plots.
only the information of the PET insert could be determined by using the measurement without the PET insert as the input and the measurement with the PET insert as the output of the system. If the two measurements with and without the PET insert are performed directly after each other and the gradient system is stable in this time period, the GIRF only includes the distortion of the PET insert.

The benefit of a corrected spiral trajectory was demonstrated, for example, in diffusion MRI (Wilm et al. 2017) and brain imaging (Kasper et al. 2017). However, the method is very flexible and can also be applied on other sequences like EPI (Wilm et al. 2015, Vanneko et al. 2016, Bollmann et al. 2017).

5. Conclusion and outlook

We measured the GIRFs up to second order spherical harmonics of the Hyperion IID PET insert. The low pass characteristic of the gradient system slightly increased, demonstrating the high gradient transparency of the PET insert. Furthermore, we measured a minor effect of the PET insert on the second order spherical harmonics. We used the GIRFs up to the first order spherical harmonics to correct a k-space trajectory of a single-shot spiral sequence and reduced blurring and distortion of the image. Slight blurring remained in the corrected image caused by either higher order gradient distortions or the inhomogeneity of the static magnetic field.

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Disclosure of conflicts of interest

The authors have no relevant conflicts of interest to disclose.

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