Optimization of encoding fields for PatLoc imaging

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Today rapid imaging in human MRI is often limited by peripheral nerve stimulation (PNS), rather then by hardware. To overcome this limitation spatial encoding with local non-bijective, curvilinear magnetic fields [1] was introduced. These fields allow for higher $\Delta B_{max}/dt$ and therefore faster imaging while staying below the PNS limit. The ambiguity of spatial encoding is resolved by using local receiver coils resulting in a PatLoc (parallel acquisition technique using localized gradients) concept [2]. To retain the property of locally orthogonal image encoding, two multipolar fields for MR imaging were proposed [3]. This abstract studies the properties of such multipolar fields, discuss their characteristics for imaging and determines the optimal multipolar fields for PatLoc imaging.

Theory

Any magnetic field inside a source-free sphere can be described by a spherical harmonic decomposition. The most relevant magnetic field component for MRI, B_z is therefore described by:

$$B_z(R,\theta,\varphi) = \sum_{n=0}^{\infty}\sum_{m=0}^{n} R^n \quad P_n^m(\cos\theta) * \left(A_{nm}\cos(m\varphi) + B_{nm}\sin(m\varphi)\right) \quad [1]$$

In the spherical harmonics expression of B_z, *R* stands for the radius and *P* for the Legendre Polynomial of (*cosθ*). To retain at least some conventional imaging properties, orthogonal imaging gradients are preferred. Pure terms of the spherical harmonics expression (coefficients n and m equal) are perfectly orthogonal, though they are not the only orthogonal fields [4] and not necessary optimal for PatLoc imaging. The pure spherical harmonics terms, like A_{22}, are not perfect for imaging because the size of the voxels at the periphery become too small and therefore there will be no measurable signal under realistic SNR conditions. Combining the pure spherical harmonics term A_{22} with a negative term of higher radial dependency, like A_{42}, will flatten the magnetic field profile at the periphery and therefore reduce the voxel size (Fig. 1). Here an attempt to determine the optimal combination of the terms A_{22} and A_{42} of the spherical harmonics expression and their corresponding near-orthogonal fields B_{22} and B_{42} is presented. Higher order terms were not considered because they require more wire for these magnetic fields to be translated into a real coil design.

$$B_zA = \alpha A_{22} + (1-\alpha)A_{42}$$
$$B_zB = \alpha B_{22} + (1-\alpha)B_{42} \quad [2]$$

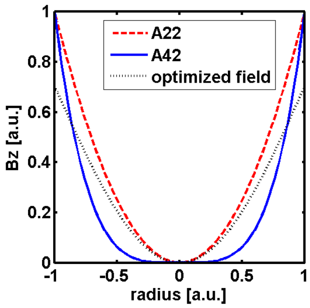

Fig. 1 field profiles

Methods

The determinant of the Jacobi matrix (Eq. 3) of the gradients contains information about the gradient strength, voxel size and angular relation of the gradients for each single voxel. As we are interested in the largest gradient strength, good angular relation between both imaging gradients and high resolution imaging, the determinant of the Jacobi matrix was subject to maximize while the global variation of the determinant is preferred to be small resulting in the following objective function (Eq. 4). This optimization was performed in a ROI which covered in plane a ring with inner radius of ¼ and outer radius of ¾ in arbitrary units. The gradient in the inner circle with radius ¼ is expected to be too small for imaging and the outer ¼ of the volume will be used by RF-coils. The optimization was implemented and performed in Matlab (The MathWorks, Inc., Natick, MA, USA).

$$J \;= \left(|\nabla B_zA||\nabla B_zB| * \cos\alpha\right) \quad [3]$$

$$objective \;= \frac{min(\sqrt{J})}{max(\sqrt{J})} \left\langle \sqrt{J} \right\rangle_{ROI} \quad [4]$$

Results

The optimal alpha was determined to be *α=0.85*. With this alpha value the magnetic field for B_zA was calculated (Fig. 2a). In Fig. 2b, the gradient profile along the radius is displayed; it reaches its maximum within the ROI, between 0.25 and 0.75 radius. In Fig. 2c the angle between both imaging gradients (B_zA and B_zB) is plotted on a pixel basis. Only at the very periphery the angle drops below 70°, but this is outside the ROI and therefore will not affect the imaging properties. Most important the Jacobi determinant of the gradients (Fig. 2d), which contains information about the voxel size reaches also its maximum within the ROI, which can be seen in Fig. 2e.

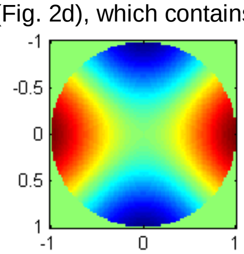

Fig. 2a field map Bz

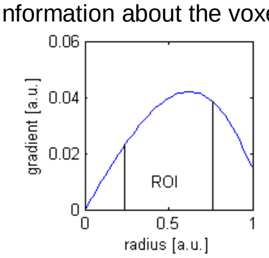

Fig. 2b gradient profile

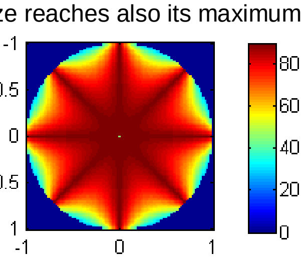

Fig. 2c angle map

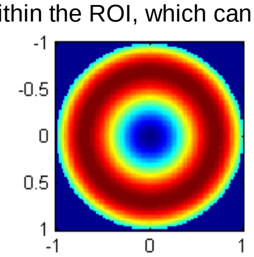

Fig. 2d Jacobi map

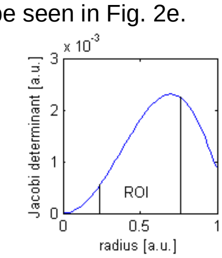

Fig. 2e Jacobi profile

Discussion

The spherical harmonic decomposition is a very powerful tool to describe magnetic fields, but by limiting the number of terms of the spherical harmonics expression interesting encoding fields may have been excluded from the optimization. As opposed to linear gradients there are more parameters that can be optimized, then gradient strength and linearity. Possible parameters for optimizing multipolar fields are the number of poles, local gradient strength and local orthogonality of the encoding gradients. Ideally, optimization of multipolar fields for PatLoc imaging needs to consider the sensitivities of the RF-coils, because this information is used to resolve ambiguities arising from the multi-polarity of the encoding fields. Here optimization was limited to fields with fourfold polarity for 2D imaging for gradient penetration depth, simplicity and implementation reasons. It is shown here that the multipolar fields with optimal imaging properties for PatLoc imaging are not the pure spherical harmonics terms, but combinations of them.

[1] Hennig et al, ISMRM, Berlin, p.453 (2007), [2] Hennig et al., MAGMA 21(1-2):5-14 (2008), [3] Welz et al, ISMRM, Toronto, p.1163 (2008),
[4] Schultz et al, ISMRM, Toronto, p.2992 (2008)

Acknowledgment: This work is a part of the INUMAC project supported by the German Federal Ministry of Education and Research, grant #13N9208