Quadrature surface coils for in vivo imaging in 900-MHz vertical bore spectrometer

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Introduction: Magnetic Resonance Imaging (MRI) continues to evolve and improve with developments in technology and techniques. Chief among these is the development of ever higher magnetic fields for increased SNR, higher spatial resolution and/or reduced imaging times, and the opportunity to exploit intrinsic MR parameters such as magnetic susceptibility and dipolar fields, as well as facilitating heteronuclear studies, *e.g.* ^{17}O and ^{23}Na. The 900-MHz, 105-mm ultra-widebore vertical magnet developed by the NHMFL and commissioned in 2005 currently provides the highest magnetic field for MRI applications (1-3). The full benefits of high field MRI, however, can only be realized if radio frequency (RF) technology can be optimized, a significant challenge with higher operating frequencies. Commercial probes are not readily available for *in vivo* imaging at 21.1 T, and existing designs at lower fields cannot simply be "scaled up" to higher operational frequencies. At 900 MHz, coil and sample geometries are on the order of the operating electrical wavelength and can cause significant B_1 inhomogeneity (4), as well as disruption of rotating field components that, unlike at low frequencies, cannot be assumed to be circularly polarized in a quadrature coil (5). This work reports on the successful development of quadrature surface coils for mouse brain imaging at 900 MHz and offers comparison to quadrature surface coils at 500 MHz.

Methods: Quadrature surface coils were designed and constructed for operation at 500 (λ_{free}=0.60 m) and 900 MHz (λ_{free}=0.33 m) with application to imaging mouse brains *in vivo*. The coils consisted of two rectangular loops conformed to a 25-mm diameter cylinder. Each loop was 25 mm in length and 12.5 mm in width for a total coil arc of 120°. Each loop contained 3 distributed capacitors and shared a common leg with a dedicated capacitor to adjust isolation. The coil was loaded with a 22-mm diameter cylinder containing material of average brain (900 MHz:ε_r=45.8, σ=0.767 S/m, λ=0.049 m and 500 MHz:ε_r=48.4, σ=0.626 S/m, λ=0.086 m). CST Microwave Studio was used to obtain B fields for export to Matlab and computation of rotating field components and resultant images. CST adaptive meshing with Fast Perfect Boundary Approximations (FPBA) was used with a tetrahedral mesh of 237,831 elements (Figure 1), minimum of 8 mesh steps per wavelength of highest frequency, and minimum edge length of 326.6 nm. For quadrature transmission, the phase of the driving voltage was assigned as coil A=0° and coil B=90°. Conversely, for quadrature reception, coil A=90° and coil B=0°. Positive and negative rotating components of transmission and reception fields were computed as (6),

$$\hat{B}_t^+ = \left(\hat{B}_{tx} + i\hat{B}_{ty}\right)/2 \quad [1] \qquad\qquad \hat{B}_t^- = \left(\hat{B}_{tx} - i\hat{B}_{ty}\right)^*/2, \quad [2]$$

where $\hat{B}_{tx}$ and $\hat{B}_{ty}$ denote the x and y components of $\hat{B}_t$ **,** respectively, and the asterisk denotes the complex conjugate. $\hat{B}_r^+$ and $\hat{B}_r^-$ were computed in the same fashion as Eqs. [1] and [2]. The transmission and reception fields were calculated as (5),

$$\left|\hat{B}_t^+\right| = \left(\left[\mathrm{Re}\left(\hat{B}_t^+\right)\right]^2 + \left[\mathrm{Im}\left(\hat{B}_t^+\right)\right]^2\right)^{1/2} \quad [3] \qquad\qquad \left|\hat{B}_r^{-*}\right| = \left(\left[\mathrm{Re}\left(\hat{B}_r^{-*}\right)\right]^2 + \left[\mathrm{Im}\left(\hat{B}_r^{-*}\right)\right]^2\right)^{1/2}. \quad [4]$$

The calculated signal intensity of a gradient echo image was then, $SI \propto W \sin(V\left|\hat{B}_t^+\right|\gamma\tau)\left(\left|\hat{B}_r^{-*}\right|\right)$, where W is proportional to water content in the voxel, V is proportional to the driving voltage, γ is the gyromagnetic ratio and τ is the pulse duration of transmission. Images were acquired on the 21.1-T ultra-widebore vertical system equipped with a Bruker Avance III console and Micro2.5 microimaging gradients. 2D gradient-recalled echo images (TE/TR = 4.5/2000 ms) were acquired at a resolution of 80 x 80 µm and slice thickness of 0.5 mm from a field of field of view of 2.04 x 2.04 cm. For linear operation, images were acquired from a single loop of the quadrature pair. For quadrature operation, a Narda hybrid coupler (Model CEL3322, 820-980 MHz bandwidth) was used to achieve transmit splitting with the required 90° phase shift and signal recombination on reception.

Results: The rotating components of the B_1 field at 900 MHz are shown in Figure 3. The intensity distribution of the positive and negative components of the transmission and reception fields vary drastically across the image space, with the overall intensity of the B_t^+ and B_r^- components the strongest (used for calculating simulated image). Beta value of 0.9 (Figure 2) in the lower center and at same location as the dark area of B_t^- predict good circular polarization. Similar results were obtained at 500 MHz. Simulated and calculated image distributions are in agreement. For 900 MHz, linear operation of a single coil element generated an SNR = 149, while quadrature operation of both elements yielded an SNR = 194, a factor of 1.3 improvement that agrees very closely with both the theoretical $\sqrt{2}$ SNR increase and the current simulations.

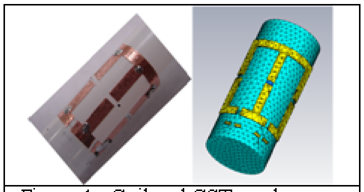

Figure 1: Coil and CST mesh

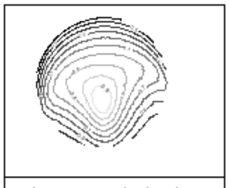

Figure 2: Polarization

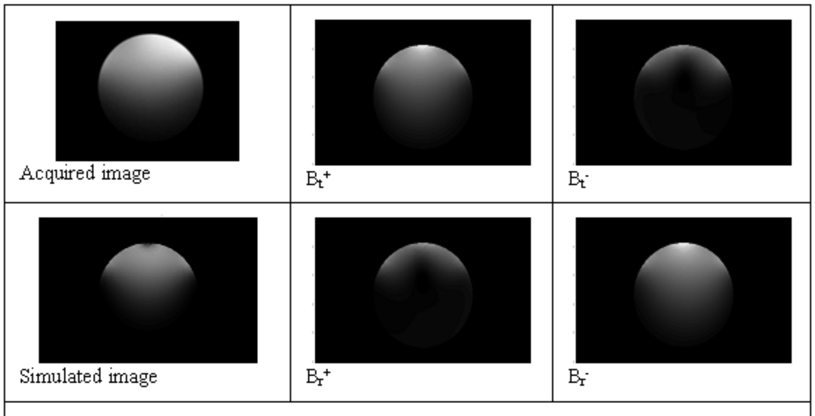

Figure 3: 900-MHz acquired image and simulated image with rotating components

Conclusions: In high field MRI, the image intensity distributions of the circulating field components are strongly affected by the electrical properties of the sample. A close examination of these components is necessary in predicting the resultant image. We have demonstrated good agreement between simulated and acquired images and that SNR gain can be achieved with quadrature surface coils intended for mouse imaging at 500 and 900 MHz. Due to the lack of electrical mesh representations of a mouse, further evaluation will be done with *in vivo* imaging. However, these initial results show promise for successful implementation of quadrature coils for *in vivo* operation.

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References

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