High and Ultra-High Field Magnetic Resonance Imaging RF Coil Designs and Optimization

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This paper addresses RF coil design for high-field (3 T $\leq B_0 < 7$ T) and ultra-high-field ($B_0 \geq 7$ T) magnetic resonance imaging (MRI), with B_0 standing for the main polarizing static magnetic field in the scanner (magnet). The principal desired objectives for the development and design of RF coils and exciting RF magnetic fields, $\mathbf{B}_1$, inside a MRI bore loaded with a human body or a phantom are: (i) strong coupling of the field with a subject and deep field penetration into the tissues; (ii) good circular polarization (CP), and more precisely, right-hand CP (RCP), of the $\mathbf{B}_1$ field inside the subject for the transverse components (normal to the axis of the bore and to field $\mathbf{B}_0$) of $\mathbf{B}_1$; (iii) high spatial uniformity of the transverse $\mathbf{B}_1^+$ field in the subject and large field of view (FOV); and (iv) low specific absorption rate (SAR). Most of the challenges related to these demands come from the inherently short, compared to low-field MRI, RF wavelengths inside biological tissues at the corresponding Larmor frequencies. For example, at $B_0 = 7$ T, with the dielectric constant typically about 50–55 in biological samples at this Larmor frequency (~300 MHz), the excitation RF wavelength inside tissues is about 14 cm or less, namely, on the order of, or smaller than, the imaged sample, resulting in a complex mix of near-field and far-field RF behaviors. The state-of-the-art RF coils are birdcage volume coils, dipole antennas, wire loops, and microstrip patches, as well as RF coil arrays, based on loop, stripline or dipole elements, fed with multi-channel RF technology such as B_1 shimming, including various transmission line TEM array designs.

We present and discuss several variations of multi-channel RF volume coil structures at 3 T, 7 T, and 10.5 T based on a subject-loaded multifilar helical-antenna RF coil. The results show that the four-channel helical-antenna 3-T exciter provides substantially better B_1^+ field uniformity and much larger FOV than any of the reported numerical and experimental results in literature that enable comparison. 7-T and 10.5-T phantom data show excellent consistency between numerical simulations and experimental results (obtained in MRI experiments at the Center for Magnetic Resonance Research, Univ. of Minnesota), with good B_1^+ field strength and uniformity, flip angle, and FOV, as well as a diverse interleaved field/phase pattern due to the four/eight helices (four/eight channels), and capability for spatial encoding, parallel imaging, and acceleration.

We also present comparative studies of various types of RF coils including array coils with different elements, phased in order to generate strong $\mathbf{B}_1^+$ filed inside the phantom. With various optimization algorithms, we can carry out $\mathbf{B}_1^+$ shimming in order to obtain more homogenous $\mathbf{B}_1^+$ field in the phantom, as well as steer and focus the field at a particular region and area inside the phantom. Some of the array coil designs provide excellent circular polarization, strong and homogenous $\mathbf{B}_1^+$ field, high efficiency, excellent relative isolation between the array elements, negligible axial field component, large FOV, and excellent possibilities for field-optimizations via RF shimming.