Optimization of Resonance Mode Stability in RF Coil Design for Very High Field MRI

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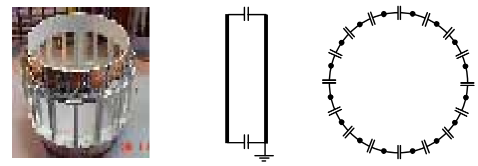
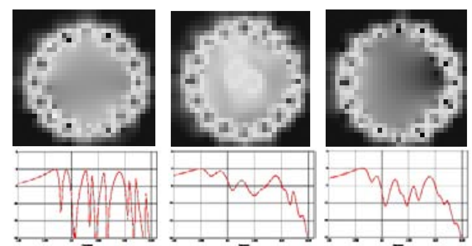
Introduction: At very high field MRI, substantial B_1 field inhomogeneity exists in the radiofrequency (RF) excitation and there is considerable interest in understanding the major factors that affect the B_1 homogeneity and to use this knowledge to optimize the design of a transmit RF coil. In recent works, dielectric resonance has been mostly investigated and the other factors have not drawn much attention [1-5]. It is the authors' opinion that the causes of field inhomogeneity should be categorized into three groups: 1) dielectric resonances within the sample; 2) cylindrical waveguide modes because of the size of the RF resonator, and 3) resonance modes generated by the RF coil. In this study, we took into account all these factors and used the resonance mode stability to evaluate the B_1 field generated in a volume coil. Based on this method, the design of a 7T volume coil was optimized and both the B_1 field homogeneity and power efficiency were improved.

Methods: Generally when operating an RF resonator, a resonance mode of interest is tuned on frequency and the other resonance modes also make a certain contribution to the current at this frequency if excited. This mode mixing decreases when the other active modes are further away from the frequency of interest and increases with the drop of Q values of those modes. In very high field MRI, the Q values of a resonance mode can be very low in loading condition due to high sample loss. Accordingly, the mode mixing effects can be much stronger at high fields than that at low fields. More importantly, the resonance mode structure of an RF resonator at high fields is dependent not only on the coil structure but also on the size of resonator and sample loading, and it is usually much more complicated than that at low fields because of the generation of many cylindrical waveguide and dielectric resonance modes. The mixing of these modes is often destructive to the B_1 field homogeneity. Therefore, a strategy to improve high field MRI is to design an RF resonator to offer good features including: 1) A single mode is generated at the frequency of interest; 2) The other modes are as far away from the frequency of interest as possible; and 3). The mixing of those destructive waveguide or dielectric resonance modes must be substantially suppressed. These features are termed as "good resonance mode stability" in our studies. Based on this concept, a 7T head volume coil was optimized. As shown in Figure 1, this coil includes 16 rung units and a ring structure on top of the rung units. The ring structure is shielded out of the imaging region. It is believed that the use of this ring structure can reduce the mode mixing from the RF coil itself, but may excite some waveguide resonance modes that are not preferable in RF excitation if not shielded out. For this reason, the TEM coil should possess some non-symmetric features in field distribution due to mode mixing if multiple-port excitation is not used for degenerating the resonance modes close to the frequency of interest. Birdcage will have much less mode mixing from the coil, but may suffer from waveguide resonance modes. All of these volume coils will substantially suffer from dielectric resonance. To prove the theory, both simulation and experiments were performed. FDTD simulation (RemCom, Inc., State College, PA) was implemented to investigate how strong the mode mixing from the coil itself may affect the field homogeneity in a TEM coil model with a two-port Quadrature excitation. Three coils, a 16-rung TEM, a 16-leg high-pass Birdcage, and an optimized volume coil, were constructed for an 11T magnet (Magnex interfaced with Bruker console, AMRIS, UF). The coil dimensions were scaled by the field strength with respect to the head coil dimensions at 7T. The standard two-port Quadrature excitation was used. The imaging performances of three coils were compared. Finally, the optimized 7T head volume coil was used to perform a human scan on a SIEMENS 7T whole body scanner.



(a) Coil (b) Rung unit (c) Ring structure

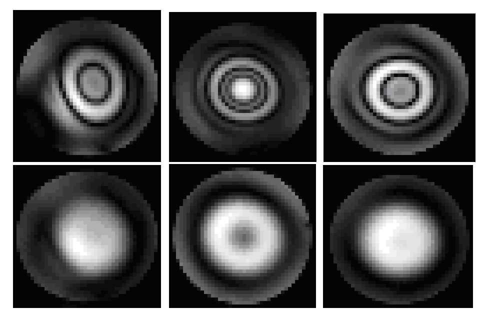
Figure 1. 7T head volume coil



(a) (b) (c)

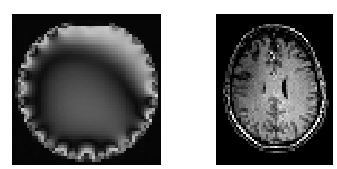
Figure 2. FDTD simulation of a TEM coil at 300MHz

Results and Discussions: Figure 2 shows the FDTD simulation results of a 16-rung TEM coil of 27cm in diameter at 300MHz. The top row gives the magnetic field inside the coil and the bottom row gives the resonance mode structure, in which the second lowest mode is the mode of interest. Figure 2(a) is the simulation without loading. It can be seen a very homogeneous field is generated. Figure 2(b) is the simulation with a human head loaded. Compared with Figure 2(a), there are significant Q drops in all the resonance modes and B_1 field is dramatically distorted. In the simulation shown in Figure 2(c), the coil is unloaded, but some resistance is used to reduce the Q values of all the resonance modes. It can be seen that the field is also distorted considerably when the Q values are comparable to those in loading condition. Such a distortion is related to the mode mixing of those resonance modes generated only by the coil because the waveguide and dielectric resonance were excluded in unloading condition. This simulation demonstrated that a good mode structure from the coil itself is important to the B_1 homogeneity in high field MRI. Figure 3 shows the experimental results using three coils on the 11T magnet. The top row is the 360° field mapping of a standard spherical imaging phantom and the bottom row is the gradient echo imaging of the same phantom. It can be seen that the TEM coil has some non-symmetric features in field mapping, which demonstrates the strong mode mixing effects. This can be improved using a ring structure as in Birdcage because more coupling between legs will increase the frequency splitting between the modes. In Figure 2(b), the Birdcage gives a symmetric field map. However, a dark spot is yielded at the center of the coil. This can be related to a non-preferable waveguide resonance mode excited by the ring structure. Figure 2(c) shows that the optimized volume coil gives much better field homogeneity in the center of the coil than the other two coils, which demonstrates the efficiency of our method in B_1 field optimization. In all the figures, it can be seen that there still exists dielectric resonance, which causes a circular dark band around the center of the phantom. It is also experimentally found that the power of a 90° pulse of the optimized volume coil is 4dB lower than that of the TEM coil, which implies that the improvement of resonance mode stability can increase the power efficiency in RF excitation. Figure 4 shows the 720° field mapping of an oil phantom and an axial slice of a human head image acquired using the optimized volume coil on a SIEMENS 7T whole body scanner. These images demonstrate the capability of this coil in generating a homogeneous field in high field head imaging.



(a) TEM coil. (b) Birdcage coil (c) Optimized design

Figure 3. Images of a circular phantom at 11T.



(a). 720° field mapping. (b) Head imaging

Figure 4. Imaging using 7T volume coil

Conclusions: This work addresses the major factors that affect the B_1 homogeneity in high field volume coil design. It is shown that the mixing of multiple resonance modes is destructive to the B_1 field homogeneity. It is experimentally demonstrated that the optimization of resonance mode stability is an efficient method to increase the B_1 homogeneity and power efficiency in a volume coil design. This strategy is also useful in the design of other types of RF coils for very high field imaging.

Reference: 1). A. Kangarlu, et. al., JCAST, 23(1999), 821-831. 2). B. Beck et. al., MRM, 51(2004), 1103-1107. 3). Q. Yang et. al., MRM, 47(2002), 982-989. 4). Collins, C.M., et. al., JMRI, 21 (2005), 192-196. 5). T. Ibrahim, et. al., MRI, 19 (2001), 219-226.