A New Approach for Magnetic Resonance RF Head Coil Design

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Abstract—In this work, a new concept in high field RF head coil design for MRI applications is presented. An 8-element phased array head coil operating at 4T is designed based on a hybrid method combining reciprocity theorem and inverse method. Both circularly or linearly polarized head coils can be designed. A FDTD/MOM calculation method is used to model the phased array head coil and to accurately calculate the RF behavior inside a human head model. The simulation results reported herein demonstrate the feasibility and flexibility of the design concept and show that, compared to conventional methods, improved B1 field homogeneity is achievable at high field.

I. INTRODUCTION

With the advent of high magnetic field MR scanners, in vivo MR studies at high magnetic fields (>3T) have shown advantages relating to high SNR and spectral resolution. At high fields, however, sample field interactions cause wavelength shortening and other effects which result in large B1 inhomogeneities [1, 2] and therefore strong intensity variations. Commonly, these appear as bright spots in the centre of the area of interest. Hence, the exigency of efficient high-frequency RF coils design has thus become a critically important factor for high-field MRI.

Several RF coils, such as TEM [3] and Cavity coils [4] have been introduced to alleviate this problem in high frequency RF volume coil and transceive phased array coils [5] has also been suggested as devices to help mitigate the B1 inhomogeneities. Recently, it has been suggested that changing the magnitudes and/or phases of transmission pulses, it can achieve beam focusing and in part attain homogenous B1 fields. These methods include optimizing the current distribution on the rungs of multi-element volume coils [6, 7] and transmitting focussed B1 field using phased array coils [8]. Another approach is to apply inverse method with pre-emphasized B1 fields [9] for the design of high frequency RF coils.

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In this work, a new method of designing RF head coils is proposed. The method is to some extent similar to the inverse method; however it uses classical reciprocity theorem instead. An elongated volume of magnetic dipoles of desired magnitudes and phases are firstly pre-set within and around a heterogeneous head phantom. These dipoles will induce current on each element of a pre-constructed 8-element phased array head coil operating at 4T. In this way, the current distribution on each element of the head coil induced by the pre-set magnetic dipoles will then transmit a homogenous B1 field that can potentially ameliorate the problematic bright spots. This method can be used to design circularly or linearly polarized RF head coils. It has several potential advantages and the simulation results reported here demonstrate it feasibility and flexibility.

II. METHODOLOGY

The strategy of using the principle of reciprocity in assessing nuclear magnetic resonance (NMR) signal strength was first introduced by Hoult [10, 11], which in the NMR context and in the simplest form stated that if a unit direct current was applied to a receiving coil and the B1 field created by it at the NMR sample was measured, the current induced in the coil by the precessing nuclear magnetic moment would be proportional to the strength of this hypothetical field.

On the other hand, the implementation of inverse method firstly purposed by Fujita and co-worker [12] and later used by Lawrence and collaborators [13, 14] for designing RF coils, suggested that if a diameter of the sensitive volume (DSV) within a predefined cylinder region was firstly pre-set with a desired RF field and thereafter utilizing target field technique, current distributions for a given coil geometry could be calculated that give the best approximation to the pre-set RF field. The current density being solved for this pre-set RF field was then used in stream function techniques, which discretizes the continuous current distributions to find the corresponding conductor patterns. Although inverse method had its success in designing RF coils, where some novel asymmetric RF coils using inverse method had been successfully designed and constructed, it had not been applied to the high field case where a heterogeneous dielectric load was present.
However, by conjoining the concepts from both reciprocity theorem and inverse methods, it implies that if one is able to construct a net magnetic moment over a volume of interest which is similar to the inverse method in pre-setting the desire RF field, the net magnetization will induce current on a pre-constructed conductor surrounding the load. The induced current on the conductor shall then reproduce the same magnetic field. Furthermore, if a heterogeneous dielectric phantom is included over the volume where the net magnetic moment is pre-set, sample induced RF perturbation and loading effect can be considered and this shall then have practical applicability of this technique for actual RF coils. Using this approach, numerical simulations involving hybrid finite difference time domain (FDTD) [15] / method of moments (MoM) [16] is employed to investigate the feasibility of designing an 8-element phased array head coil operating at 4T.

The design of the 170MHz (4T), 8-element phased array head coil begins by pre-constructing the 8 elements using commercially available software FEKO (www.feko.co.za), a full wave, MoM based RF simulation program. Each element has length of 240mm and is positioned 45 apart around a circumference with diameter of 300mm as shown in Fig. 1.

In order to take into account coil-sample and field-tissue interaction, an approximate, heterogeneous volumetric human head phantom consisting of 3 layers of differing dielectric properties is constructed in MOM as shown in Fig. 2. Layer 1 has dielectric properties that represent skin, skull, fat and muscle, layer 2 is the cerebrospinal fluid (CSF) and layer 3 represents grey and white matters.

The head phantom is then placed within the 8-element phased array head coil and magnetic dipoles are used to simulate the net magnetic moment. Magnetic dipoles are arranged such that they occupy the whole volume of the head phantom. In MRI, signal in any given voxel originates from that voxel, hence in the MoM simulation, the magnetics dipoles are set on a voxel by voxel basis. In additional, in any RF resonator design, the uttermost importance is to achieve a homogenous magnetic field over a predefined DSV. In this case, the objective is to attain a homogenous magnetic field over the volume of the head phantom. Therefore, the magnitudes of the magnetic dipoles are all set to 1 A/m.

To demonstrate the flexibility of the purposed technique, circularly and linearly magnetic dipoles are simulated for the design of both circularly and linearly polarized RF head coils. Fig. 3 shows the overall setup including the magnetic dipoles in MoM for both polarizations.
Once the magnitudes and phases of the current distribution on each segment of the 8 element induced by the pre-set magnetic dipoles are calculated in MoM, an in-house FDTD package [17] is used to investigate the RF fields inside an accurate human head model excited by the calculated currents. The model is obtained from the U.S. Air Force Research laboratory, (http://www.brooks.af.mil/AFRL/HED/hedr/).

To implement the FDTD calculation, the MoM-calculated currents are firstly mapped onto FDTD cells with a 3mm\(^3\) uniform grid and the entire computational domain is divided into \(N_x \times N_y \times N_z = 135 \times 134 \times 123 \approx 222.5 \times 10^5\) Yee cells. Ten perfectly matched layer (PML) with a parabolic conductivity profile are included in the FDTD simulation and located on the six open sides, which are positioned at the anterior, posterior, the 2 lateral sides, the top and the bottom planes with respect to the head model.

The outputs of the FDTD calculations are the magnitudes and phases of the sinusoidal steady-state electric and magnetic fields (EMF), which are registered within a period of the operating frequency. After the FDTD calculation transient response has passed, the peak EMF data are recorded. The elapsed (transient) time is also recorded to calculate the phases of the steady EMF. In this way, the complex electric and magnetic field vectors at all vertices on the grid of FDTD cells can be generated.

Following the principle of reciprocity, the transmission field and reception field can be calculated [18] by

\[
\hat{B}_t = \left( \hat{B}_r + i \hat{B}_r \right)/2 \quad (1)
\]

\[
\hat{B}_r = \left( \hat{B}_r - i \hat{B}_r \right)/2 \quad (2)
\]

where (1) and (2) are the two orthogonal components of the complex magnetic field calculated by FDTD; an asterisk denotes a complex conjugate. Solving (1) and (2), we obtain the transmission and reception \(B_1\) fields, from which signal intensity (SI) can be calculated [18] by

\[
SI = i\omega M_0 \sin \left( \gamma \tau \right) \left| \hat{B}_t^{\perp} \right| \left| \hat{B}_r^{\perp} \right| \quad (3)
\]

where \(\omega\) is the operating frequency, \(M_0\) is the initial magnetization, \(\gamma\) is the gyromagnetic ratio, \(\tau\) is the RF pulse duration of the transmission field, \(K\) is a dimensionless constant to adjust the flip angle and the integer \(n\) is sequence-dependent and is set to 1 for gradient echo sequences.

Figure. 4 shows the FDTD calculated magnetic fields using the current induced on the 8 elements by the pre-set magnetic dipoles in MoM. To further show that the method proposed here in designing the 8-element phased array head coil can alleviate spurious intensity variations, it is compared with a 16-leg linear lowpass birdcage, which is shown in Fig. 5 with its accompanying SI plot taken from the mid section along the lateral side of the brain image.

Fig. 4. The FDTD calculated magnetic field. (a) Using the current induced by circularly pre-set magnetic dipoles. (b) Using the current induced by linearly pre-set magnetic dipoles.

Fig. 5. A comparison of SI between the newly designed (a) circularly polarized and (b) linearly polarized head coil with (c) a 16-leg linear lowpass birdcage coil. (d – f), its accompanying SI plot taken from the mid section and along the lateral side of the brain image.
IV. DISCUSSION

In this work, the design of an 8-element phased array head coil using combined reciprocity theorem and inverse method has been demonstrated. Illustrated in Fig. 4, a homogenous $B_1$ field is obtained using the current on each element induced by the circularly and linearly pre-set magnetic dipoles. In additional, comparing the three images and the $SI$ plots shown in Fig. 5, it can be readily seen that a homogenous distribution of $SI$ across the images is achieved with the circular and linear polarized 8-element phased array head coil as compared to the birdcage coil. The method suggested herein reduces large variations in intensity resultant from tissue/field interactions as it is already been accounted for in MoM with the inclusion of the heterogeneous human head phantom and hence to some extent mitigates the “bright spots” effect.

Unlike the traditional inverse method, where we first set the RF field which will then calculate the current map and following that the structure of the head coil, the method suggested here gives us the flexibility to design the structure of the head coil and later find the optimum current distribution induced by the target field. Thus we have total control over the structure of the head coil. This method is not confined to straight element designs and can be extended to surface coil technology.

Lastly, the ability to set the desired field either circularly or linearly polarized provides a valuable advantage in giving us an option in choosing to design either a circularly or linearly polarized head coil. Moreover, the ability to set the magnitude of the magnetic dipole will mean that if certain area of the voxel is set with higher magnitude as compare to the rest of the surrounding magnetic dipoles, beam focusing for hyperthermia application can be performed or otherwise if it is set with lower magnitude, pre-emphasized $B_1$ field for the design of RF coil can be implemented, which has the potential to further improve the system.

V. CONCLUSION

A new concept based on a combined idea from reciprocity theorem and an inverse method for RF coil design is presented in this work. Circularly and linearly polarized 8-element phased array head coils have been designed and the simulations demonstrate the feasibility and flexibility of the method. The ability to have control over the structure of the RF coil and achieve improved $B_1$ homogeneity at high frequency has been theoretically demonstrated. Experimental verification of the designs will be reported in the future.

REFERENCES