Why Does the Radiative Antenna Have no B1 Twisting at 7T? Framework for and Applications of a Conceptual "Mirror Current" Model of Coil-Tissue Interactions

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Introduction: It has long been observed that the B_1 fields of RF coils in conductive objects "twist" at high operating frequency. Even for perfectly symmetrical objects, notable asymmetries appear in coil transmission and reception sensitivity patterns. These asymmetries represent one of the significant challenges to achieving homogeneous excitations at high field strength. Although techniques such as parallel transmission and RF shimming can compensate to some extent for field twisting, they also increase engineering effort and complicate workflow. A solid understanding of the mechanisms behind field twisting would be useful in the design of coils which either exploit or minimize that twisting. Transmit and receive asymmetries at high magnetic field strength have rightly been attributed in a broad sense to the circularly-polarized nature of the MR experiment, and to the interactions between RF coils and the imaged body. However, the prediction of particular asymmetries has generally relied upon numerical simulations, and the general conditions under which such asymmetries might or might not appear have not been spelled out in intuitive terms. Recently, it has been noted [1] that the fact that magnetically induced "eddy" currents in the sample lag the currents in the coil by 90° in phase, as required by Faraday's law, is the origin of net RF magnetic fields whose degree and sense of circular polarization can vary spatially, and which can therefore result in transmission and reception patterns that appear to twist in opposite directions, reflecting the opposite effective polarization of transmit and receive sensitivities [2]. On the other hand, phase lag alone is not sufficient to cause asymmetries, as one particular example illustrates clearly: a recently proposed radiative antenna displays no appreciable B_1 twisting at 7T, even when loaded with a high conductive sample in which eddy currents surely travel [2]. In this work, we use full wave electromagnetic field simulations and corresponding simple conceptual constructions involving mirror currents to highlight another key factor contributing to field twisting: the presence or absence of 90° spatial offset between the orientations of source and induced magnetic fields. This framework is used to explain the observed sensitivity patterns of the radiative antenna and other exemplary coils.

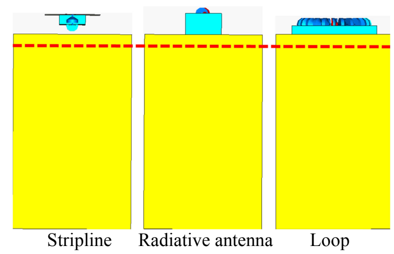

Fig. 1: Three different coils loaded by the same phantom. The dotted line marks a depth of 20mm within the phantom, and indicates the plane in which mirror currents are analyzed.

Methods: When a coil is loaded by a conductive sample, current is induced in the conductive sample in response to applied RF fields. Instead of characterizing this current as "eddy current", we shall refer to it here as "mirror current" since, like current induced in a ground plane which emulates a mirror current, it too respects the boundary conditions of the conductive sample, and in fact is physically distributed therein. The induced current pattern in a sample with finite conductivity is more difficult to compute than in the case of a perfect ground plane, but it may indeed be derived from Ampere's law:

$$J_{tot} = \nabla \times H = (\sigma + j\omega\varepsilon)\cdot E \qquad (1)$$

Here, σ is the conductivity and ε is the permittivity of the sample.

Using the FDTD method (Microwave Studio, CST, Germany), we simulated three different coils geometries: stripline, loop and radiative antenna. The three coils are loaded by the same phantom, with uniform σ=0.63S/m and ε_r=78.5. The stripline is placed 2cm away from the phantom, and the substrate between the strip and the ground plane is acrylic (ε_r=2.2). There is a large dielectric substrate with high permittivity (ε_r=37) between the radiative antenna and the phantom, as specified in [3]. The substrate between the loop and the phantom is 2cm-thick acrylic. All these three setups are tuned and matched in the simulations as in the experiments, and the convergence is -40dB in each setup. At 20mm depth in the phantom, indicated by the virtual red line in Figure 1, the total current induced in the sample is plotted. Moreover, the interaction between the B field induced by this mirror current and that induced by the coil current also analyzed.

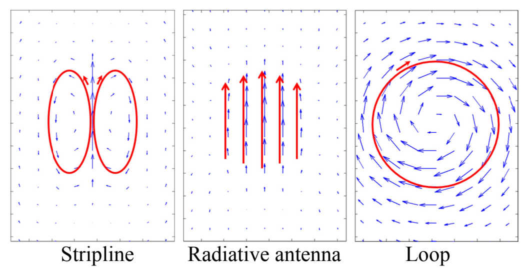

Fig.2 Mirror current induced in the phantom

Results: As shown in FIG. 2, the mirror current in the shielded stripline system resembles two adjacent loops, whereas the mirror current in the radiative antenna resembles multiple parallel current strips, with the center strip having the highest current amplitude. By contrast, the mirror current in the loop system resembles a distributed loop. The magnetic field lines created by the mirror current in the phantom and those created by the current in the coil are shown in FIG. 3 in the central axial plane. It can be seen that in the stripline system, elliptically polarized fields are created, clockwise on one side and anti-clockwise on the other side. In the radiative antenna system, since the mirror current is broadly distributed and parallel to the source current, the magnetic field lines travel largely in parallel, and thus the combined B fields are still linearly polarized, as we can see from Figure 4. In the loop system, the combined B fields rotate clockwise on one side and anti-clockwise on the other side. At some points, the magnetic field lines created by the mirror current in the phantom and the current in the coil are perpendicular to each other, forming fully circularly polarized fields with opposite senses on different sides of the phantom.

Conclusions: Mirror currents induced in the sample interact with currents in the coil, and these interactions can create circularly polarized fields and anti-circularly polarized fields in the same object, resulting in asymmetrical B_1+ and B_1- in the images even in a perfectly symmetrical object. Efficient creation of circularly polarized fields requires 90 degree differences in spatial orientation as well as 90 degree temporal phase offset. Since the fields in the central area beneath the radiative coil system do not have 90 degree spatial offset, the B_1+ and B_1- are not twisted in this area. Though a strict separation of eddy currents from source currents is somewhat artificial from an electrodynamic point of view, quick geometrical constructions of "mirror" current configurations for prospective coil designs (backed up of course by rigorous electrodynamic simulations) can yield insight into expected sensitivity patterns, and can guide the design of coils with desirable symmetry properties.

[1] Collins CM, et al, MRM 47: 1026-1028 (2002) [2] Collins CM, et al, MRM 65: 1470-1482, 2011 [3] Raaijmakers A, et al, ProcISMRM2010, p40

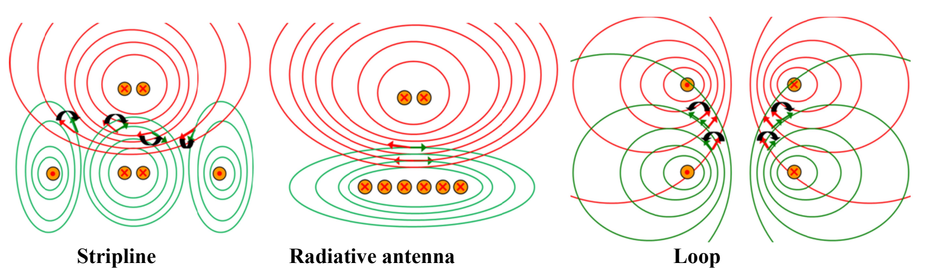

Fig.3 B fields (green lines) induced by the mirror current in the phantom and B fields (red lines) induced by the current in the coil, "•" indicates current out of the paper, and "×" indicates current out of the paper. These two kinds of B fields are phase-shifted from each other by 90degrees.

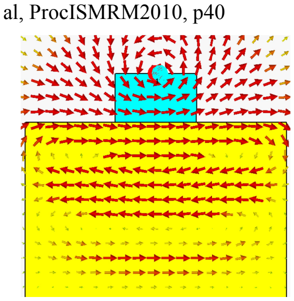

FIG. 4: B field vectors in the radiative antenna system.