Ideal current patterns correspond to larger surface coils with use of high permittivity materials

Manushka V Vaidya[1,2], Gillian G Haemer[1,2], Giuseppe Carluccio[1], Dmitry Novikov[1,2], Daniel K. Sodickson[1,2], Christopher M. Collins[1,2], Graham C. Wiggins[1,2], and Riccardo Lattanzi[1,2]

[1]*Center for Advanced Imaging Innovation and Research, and Center for Biomedical Imaging, Department of Radiology, New York University School of Medicine, New York, NY, United States,* [2]*Sackler Institute of Graduate Biomedical Sciences, New York University School of Medicine, New York, NY, United States*

TARGET AUDIENCE: **RF Engineers and anyone interested in using dielectric materials for improved coil performance**

PURPOSE: Dielectric materials with high relative permittivity ($\varepsilon_r > 80$) interposed between RF coils and the imaged body can improve signal-to-noise ratio (SNR) in magnetic resonance (MR) applications[1, 2]. However, it is unclear precisely how dielectric materials affect the electromagnetic (EM) field to achieve the observed advantage. Ideal current patterns are calculated to obtain the best possible performance, i.e. the ultimate intrinsic SNR (UISNR), at a position of interest within the imaging sample. The highest performing RF coil designs mimic the characteristic shape and behavior of these ideal patterns[4, 5]. In this work, we use ideal current patterns as a tool to understand how dielectric materials affect electromagnetic field behavior and improve coil performance. Given that the UISNR does not change in the presence of a lossless dielectric layer[6], we hypothesized that the ideal current patterns change in the presence of a dielectric material to maintain optimal performance.

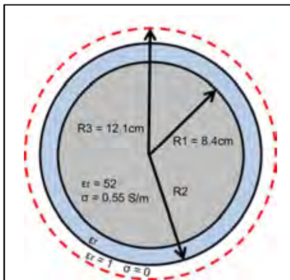

Fig. 1: Simulation set-up at 7 T. The dielectric layer (blue) surrounds the spherical sample (gray). The thickness and ε_r of the layer was varied for different cases. The current density was defined at the red dashed line

METHODS: An in-house multi-layer simulation framework based on dyadic Green's functions was used to calculate the ideal current patterns for a homogenous dielectric sphere with and without a surrounding continuous layer of dielectric material (ε_r = 1000) at 297.2 MHz (Fig. 1)[3, 6]. The ideal current patterns were calculated for a central voxel (0.25 cm from the origin) and for voxels at two off-center positions (3.4 cm and 2.4 cm from the origin). The thickness of the dielectric material was varied from 0.8 cm (corresponding to λ /4) to 3.2 cm (corresponding to λ). An expansion order of l_{max} = 65 was used to ensure convergence of the UISNR calculation for every voxel.

RESULTS: In all cases, the UISNR at the voxel of interest did not change in the presence of the dielectric layer, though the ideal current patterns were indeed perturbed with the dielectric material present. **Central voxel:** For optimal imaging of the central voxel, the ideal current patterns form two distributed loops, which rotate around the sample at the Larmor frequency. The only noticeable change with addition of the dielectric layer was a delay in phase, as seen in **Fig. 2** (comparing the first and second row). To confirm that this effect was due to a time delay in signal reception at the coil surface due to propagation through the additional dielectric layer, the velocity of EM propagation within the dielectric material ($v = 1/\sqrt{\mu_0\mu_r\varepsilon_0\varepsilon_r}$) was converted to phase delay based on the wavelength ($\lambda = v/f$) and thickness of the layer. This calculated phase delay, 90^o for 0.8 cm thick dielectric layer, roughly matched the apparent phase shift in the ideal current pattern when the dielectric layer was added. For a 3.2 cm thick layer (corresponding to λ), the results matched the case with air (not shown). Calculations for ε_r = 500 gave similar results (not shown). **Intermediate voxel:** For optimal imaging of a voxel at an intermediate distance from the center, the ideal current pattern alternates between a distributed loop and figure eight over time, but the ideal current pattern covers a larger area when the dielectric material is present (Fig. 3, A vs. B and D vs. E). The result indicates that for off-center locations, a larger sized surface coil should produce SNR closer to the optimum value when a dielectric material is present. Note that the size of the ideal current pattern for the case with high dielectric for imaging a voxel at 3.4 cm is similar to the case with air at 2.4cm (C vs. B and F vs. E.).

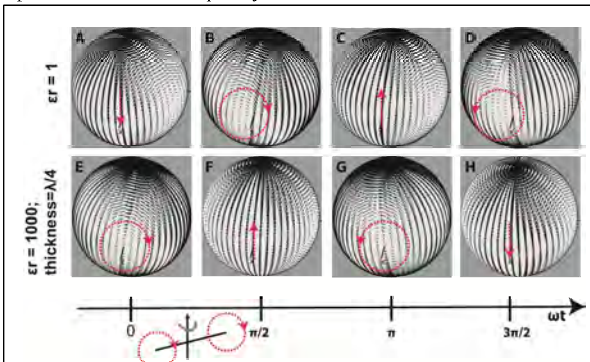

Fig 2: Phase delay in the ideal current patterns for the central voxel. Note that row 2 lags row 1 by 90^o, for a high dielectric material with thickness of $\boldsymbol{\lambda/4}$. Schematic shows the direction of rotation of distributed loops around the axis.

DISCUSSION AND CONCLUSIONS: The shape of the ideal current patterns is dictated by the need to track (or, from the point of view of reciprocity, to reproduce in transmission) the precessing field of a spin at the target location, while minimizing sensitivity to noise from the entire sample[3]. Therefore, the patterns change from two distributed loops rotating around the z-axis at the Larmor frequency (i.e. volume quadrature) for a voxel of interest at the center to a distributed local figure-eight and loop (i.e. surface quadrature) that reduces in size as the voxel approaches the surface. The results of our current study validate our hypothesis that the ideal current patterns change in the presence of high permittivity materials. For imaging a central voxel, a dielectric layer introduces a uniform rotational phase delay to the ideal current patterns, which does not impact performance, since in this case the dielectric layer completely surrounds the sample. As there is a time delay associated with the EM field propagation through the dielectric layer, the ideal current patterns are correspondingly delayed with respect to the precession of the spin at the center, which results in the observed rotational delay. Since all points on the spherical current surface are equidistant from the center, the size and shape of the distributed pattern is unchanged with addition of the dielectric. For a voxel at an intermediate distance from the center, the most notable difference with the addition of a high permittivity material is the larger distribution of the ideal current pattern (Fig. 3). While multiple small receive coil elements are required for high coil performance[7], our results suggest that with dielectric materials larger and fewer surface elements in an array may be needed to approach the UISNR at off-center positions. This increase in size of the ideal current patterns may be a consequence of a time delayed adjustment in the ideal current patterns, or could be due to an effective increase in electrical distance between the current density position and the sample. Another alternative explanation is that larger sized current patterns maximize the receive (B_1^-) field with reduced penalty of noise reception ($i.e. \int \sigma \mathrm{E}\cdot\mathrm{E}\,\mathrm{d}v$), because of reduced E fields in the sample. Our future work will explore these hypotheses and evaluate coil performance for different coil geometries with radii derived approximately from the ideal current patterns. Our observations here provide insight into the behavior of the electromagnetic fields and provide a method to predict potential high-performance coil designs in the presence of dielectric materials.

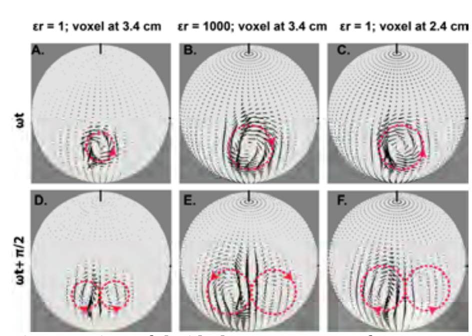

Fig 3: 3D views of the ideal current patterns for an intermediate voxel. The thickness of the dielectric layer is 1cm. The ideal current patterns interchange between a loop and figure eight over time. The larger size of the distributed pattern in B vs. A indicates that larger coils are optimal with the high permittivity material present, while the size in C vs. A (both ε_r =1) implies that larger coils are optimal for imaging locations further from the surface.

REFERENCES: 1) Webb et al., C MR Part A (2011)38A (4):148-184 2) Yang et al., JMRI (2013)24(1):197-202. 3) Lattanzi et al., MRM (2012) 68(1):286-304 4) Wiggins et al., ISMRM 2012 #541 5) Chen et al., ISMRM 2014 #402 6) Lattanzi et al., ISMRM 2014 #4818 7) Weisinger et al., ISMRM 2005 #672