3D curved electric dipole antenna for propagation delay compensation

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Target audience: Radiofrequency (RF) engineers, anyone interested in high field RF coils, parallel transmit or high field imaging.

Introduction: For a body-sized phantom at 7 Tesla, the ideal current patterns for curl-free current modes display V-shape distributions due to the need for phase evolution along the axial direction (z) to account for propagation delays to or from the central region of interest[1,2]. Previous studies have shown that either bending the electric dipole into a V to better follow the phase evolution, or shortening a straight dipole to reduce phase cancellation, helps to mitigate destructive interference of signal, and therefore to increase transmit efficiency or SNR, at the central point of interest[3]. Meanwhile, use of a dielectric substrate with electric dipole coils has been explored by various research groups[4,5]. However, use of a dielectric substrate for the specific purpose of compensating for propagation delay has not been demonstrated until now. Here we describe a novel 3D curved electric dipole antenna design constructed on a dielectric substrate to compensate for propagation delays and increase central B_1^+ efficiency. We evaluated the performance of this new type of design in simulations, and constructed an early prototype for experimental evaluation.

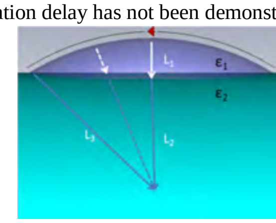

Figure 1: 3D curved dipole to compensate propagation delay

Theory: At the 7 Tesla Larmor frequency (~300 MHz), the wavelength of RF traveling in human tissue is smaller than human body dimensions (λ = 12.5 cm for ε_r = 64). This short wavelength gives rise to the familiar problem of B_1^+ inhomogeneity due to destructive interference of fields in certain regions [5]. For any antenna, and in particular for a traditional linear electric dipole antenna, fields induced by different parts of the antenna located at different distances from the center of a body require different amounts of time to reach the point of interest. For a 40 cm straight z-directed dipole placed on top of a 290 mm diameter cylindrical phantom with ε_r = 64, the phase difference due to differential propagation delay for fields generated at the center and at the ends of the antenna is 294°. This phase difference is reduced to 90° when the dipole is shortened to 20cm. The varying propagation delay along the length of the antenna can result in field cancellation and can compromise coil performance. To compensate for this differential propagation delay, we propose a 3D curved dipole as shown in Fig 1, placed atop a curved dielectric substrate with relative permittivity ε_1. When this arrangement is placed on the surface of a cylindrical phantom with relative permittivity ε_2, and when the path length to the center of the phantom from a point at the center of the dipole is denoted by L_1+L_2 and the path length from the end of the dipole to the center of the phantom is denoted by L_3, propagation delay compensation is achieved if $L_1 * \varepsilon_1^{1/2} + L_2 * \varepsilon_2^{1/2} = L_3 * \varepsilon_2^{1/2}$. In this situation, the fields induced by different parts of the electric dipole antenna will reach the center of phantom in phase, and optimal summation will be achieved in the center.

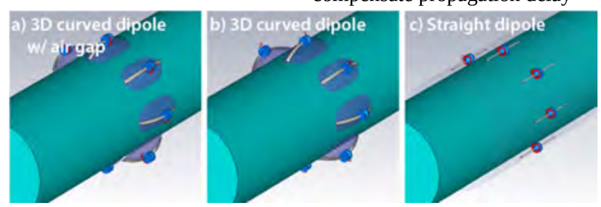

Figure 2: simulation configuration for various dipole arrays

Methods: Electrodynamic simulations were performed with Microwave Studio (CST, Darmstadt, Germany). For a single 3D curved dipole, a strip of conductor 10 mm wide was bent on top of a bubble shaped substrate which was 190 mm long, as shown in Fig 1. The length of the conductor was adjusted so that the 3D curved dipole had a 190 mm horizontal length. The electric dipole was fed in the center, and lumped element inductors by the feed point were used for coil tuning. Distilled water (ε_r = 78.4, σ = 5.55e-6 S/m), was used to model the substrate, and the height of the substrate, L_1 = 27 mm, was calculated according to the delay compensation formula derived above. Eight z-directed 3D curved dipoles were placed circumferentially around a cylindrical phantom (ε_r = 81.81**,** σ = 0.604 S/m) measuring 29 cm in diameter and 120 cm in length, as shown in Fig 2(b). As a previous study has shown that attaching substrate to the phantom produces high local SAR close to the surface of the phantom[7], a 3D curved dipole array with 5mm air gap between the substrate and the phantom was also simulated, as shown in Fig 2(a). A straight dipole array with lumped element inductors by the feed point (Fig 2(c)) was also simulated for comparison. All the dipole elements were 190 mm in length, and were tuned and matched to 297.2 MHz.

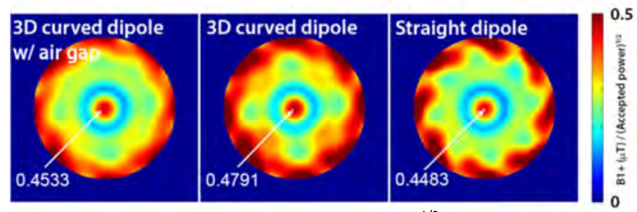

Figure 3: B_1^+ normalized by (accepted power)$^{1/2}$ comparison

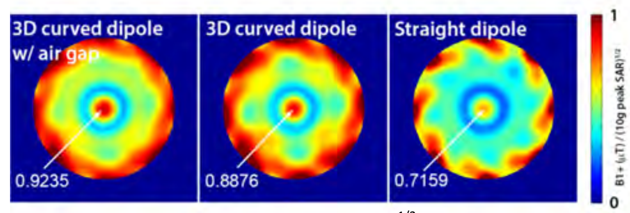

Figure 4: B_1^+ normalized by (10g peak SAR)$^{1/2}$ comparison

Results and Discussion: Figure 3 shows the B_1^+ (normalized by square root of total delivered power) in the central transversal slice for different arrays. The 3D curved dipole array was the best among the three designs, and produced 7% higher B_1^+ in the center when compared to the straight short dipole. When B_1^+ was normalized by the square root of 10g peak local SAR rather than total power, as shown in Figure 4, the 3D curved dipole outperformed the straight short dipole by 23%. However, the design with an air gap had the best central performance with this normalization, and outperformed the straight dipole array by 29%, while also providing a more uniform B_1^+ distribution across the plane.

Conclusions and Future Directions: We have demonstrated in simulations the B_1^+ benefits of compensating for the propagation delay of fields produced by points along an electric dipole antenna. Unlike the bent dipole we proposed last year, which needs to be bent in opposite directions for transmit or receive optimization, the innovative 3D curved dipole design would improve both B_1^+ and SNR performance, which makes it a promising approach as a transceiver. A prototype of 3D curved dipole was also constructed on a 3D-printed bubble-shaped substrate 35 mm high and 200 mm in length, as shown in Figure 5. The substrate was filled with distilled water. A dipole was bent following the curve of the bubble with lumped element inductors by the feed point for tuning. In order to validate the simulations reported here, experimental evaluation of the performance of the 3D curved dipole as compared with straight dipoles is ongoing.


Figure 5: Constructed 3D curved dipole prototype with substrate filled with distilled water

Reference: [1] Lattanzi R. MRM 68:286–304 (2012) [2] Wiggins G. ISMRM 2012 p541 [3] Chen G. ISMRM 2014 p402 [4] A. J. E. Raaijmakers, MRM 66:1488–1497 (2011) [5] Winter L. PLoS One 2013 8(4) e61661. [6] Hoult D. JMRI 12:46–67 (2000) [7] Ipek O. Concepts Magn. Reson., 43B: 1–10.