4086

Dielectric Resonators and Dipole Antennas Combined: New Approach in Radio Frequency Coil Design for Ultrahigh Field MRI

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Synopsis

Dielectric resonators (DR) can be advantageous over conventional loop elements, especially in ultrahigh field MRI. We noticed, that it is possible to combine DR in transverse electric mode with dipole antennas (DA), by placing them exactly above each other. In this study we explore the benefits of such combination in a multi-channel array configuration. We present the results of electromagnetic field simulations in which we compared an 8/8-channel DR-DA array with: 8-channel loop array, 8-channel DA array and 8/8-channel loop-DA array.

Introduction

Dielectric resonators (DR) are a promising alternative to conventional loop elements in radio frequency (RF) coil design for ultrahigh field (UHF) MRI[1]. Using DR, that have a very high dielectric permittivity, can provide higher magnetic field concentration closer to the resonator and reduced specific absorption rate (SAR) vs. a loop element of similar size[2]. Dipole antennas (DA) can provide higher transmit efficiency in deeper regions of human body[3]. We have noticed, that magnetic field vectors of DR in transverse electric ($TE_{01\delta}$) mode and DA are orthogonal to each other what results in particularly high level of isolation when one element is placed exactly above the other one. Consequently, DR and DA can be used as a building block of a multi-channel array that can benefit from all of the advantages of DR, DA and a combination of both (DR-DA). In this study, we have designed an 8/8-channel DR-DA array, performed electromagnetic field (EMF) simulations in cylindrical phantom, and benchmarked the 8/8-channel DR-DA array against: 8-channel loop array, 8-channel DA array and 8/8-channel loop/DA array.

Methods

EMF and specific absorption rate (SAR) simulations in cylindrical phantom (radius = 75 mm, length = 250 mm, conductivity σ = 0.4 S/m, dielectric permittivity ε_r = 80) were performed using Sim4Life 4.4 (ZMT AG, Switzerland). The dielectric block has following electrical properties: σ = 0.2 S/m and ε_r = 1070. The size of the block is (90x44x5) mm^3. The loop elements have the same size in plane as dielectric blocks and conductor width is 5 mm. The dipole antennas (total length = 210 mm) were fractionated using two inductors (60 nH). All of the arrays presented in this study were driven in circularly polarized (CP) mode (phase increment/element = 45°) and compared in terms of transmit field ($B_1^+/\sqrt{P_{in}}$) and SAR efficiency ($B_1^+/\sqrt{SAR_{10g}}$). The 8/8-channel DR/DA array was driven in two different CP modes: only DR elements (TX-DR) and only DA elements were transmitting RF (TX-DA). TX-DR mode was compared with 8-channel DR array and 8-channel loop array. Finally, the 8/8-channel DR/DA was benchmarked against 8/8-channel loop/DA array.

Results

Magnetic field (H-field) vectors of DR ($TE_{01\delta}$ mode) and DA were orthogonal to each other (Figure 1). Reduced value of electrical conductivity in 8/8-channel DR/DA array, despite increased intra-element coupling, lead to significant gains in transmit and SAR efficiency, especially in surface regions (Figure 2). The 8/8-channel DR-DA array was tested in two different scenarios TX-DR and TX-DA. In TX-DR, B_1^+ and SAR efficiency of the 8/8-channel DR-DA array was significantly higher than an 8-channel loop array of similar size, up to the penetration depth of 4 cm (Figure 3). Placing DA elements over DR elements did not degrade the performance of 8-channel DR array. 8-channel DA array provided much higher transmit field efficiency in the center than 8-channel DR array and 8-channel loop array (Figure 3). In TX-DA, the 8/8-channel DR-DA array still provided very good B_1^+ in deeper regions: only 8% lower transmit efficiency than 8-channel DA array and 2% lower than 8/8 loop-DA array (Figure 4). The 8/8-channel DR/DA array performs better in surface regions in terms of B_1^+ efficiency than 8/8-channel DA/loop array (Figure 5), but was outperformed in deeper regions (loop element contribution).

Discussion and Conclusion

Our simulations show that it is possible to combine dielectric resonators driven in $TE_{01\delta}$ mode with dipole antennas. Placing both elements symmetrically above each other resulted in negligible coupling, because the EM fields produced by DA and DR were complementary. We showed, that B_1^+ efficiency of 8/8-channel DR-DA array, due to is duality, outperforms: 8-channel DR array in deeper regions, 8-channel loop array in surface (DR) and deeper (DA) regions, and 8-channel DA in surface regions. Moreover, 8/8-channel DR-DA array provides higher B_1^+ efficiency in surface regions than 8/8-channel loop/DA array, but lower B_1^+ efficiency in deeper regions. The latter can be easily explained, because in our proof-of-principle study we used DR of a very high ε_r. DR can be still optimized (geometry, σ, ε_r), so that it approaches loop performance in deeper regions. The possibility to optimize DR and combine it with DA might not only be relevant at 7.0 T, but also at higher field strengths (above 10.5 T), because the number of capacitors and inductors increases with resonance frequency, and DR elements do not require these components at all. In this work we focused on 8/8-channel array DR/DA, but our approach can be translated into other array configurations including lower and higher number of elements. We anticipate B_1^+ optimization in which DA could be used to further improve SAR efficiency. The expected gains in B_1^+ efficiency can not only advance state-of-the-art MR spectroscopy in surface regions of interest like cerebral cortex, muscle and skin, but also provide high B_1^+ efficiency in anatomical regions that are located deeper.

Acknowledgements

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References

1. SA Aussenhofer, AG Webb, An eight-channel transmit/receive array of TE01 mode high permittivity ceramic resonators for human imaging at 7T, J Magn Reson, 2014 Jun; 243:122-9. 2. TPA O'Reilly, et al., Modular transmit/receive array using very-high permittivity dielectric resonator antennas. Magn Reson Med, 2018 Mar;79(3):1781-1788. 3. AJ Raaijmakers, et al., The fractionated dipole antenna: A new antenna for body imaging at 7 Tesla, Magn Reson Med, 2016 Mar;75(3):1366-74.

Figures

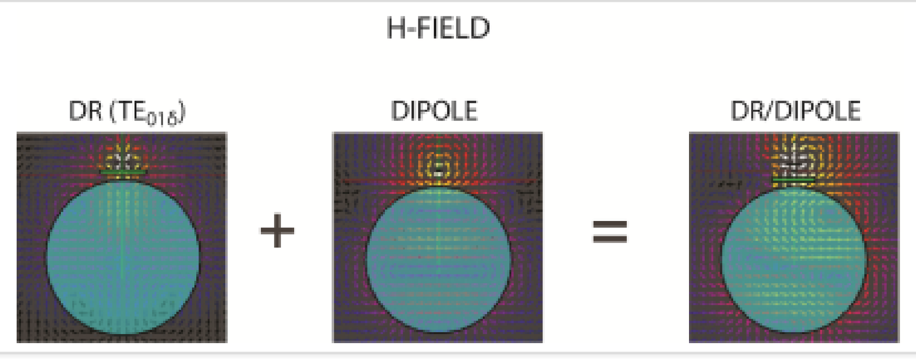

Figure 1: Cylindrical phantom (σ=0.4 S/m, diameter = 75mm) in axial view: H-field distribution. DR and DA H-fields are linearly polarized and orthogonal to each other. The combination of both results in a circularly polarized-like magnetic field.

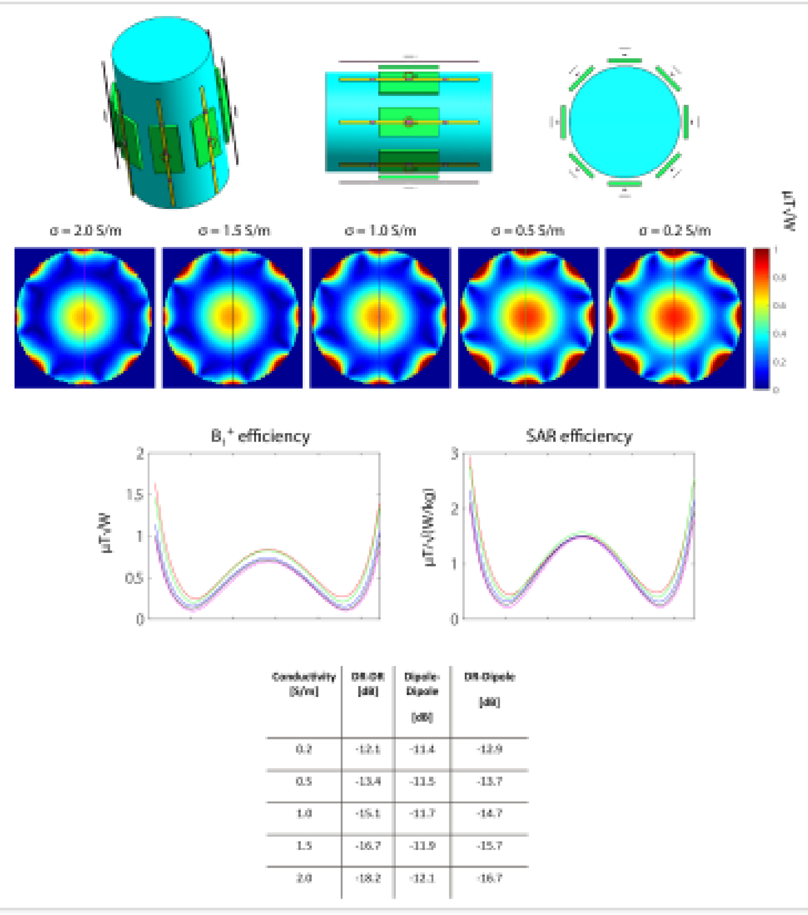

Figure 2: Transmit field and SAR efficiency of an 8-channel dielectric resonator-dipole array placed around a cylindrical phantom as a function of varying electrical conductivity value (0.2, 0.5, 1.0, 1.5 and 2.0 S/m). B_1^+ shimming: phase increment = 45° per element. The table below shows coupling between elements of 8/8-channel DR-DA array as a function of DR conductivity. DR-DR – coupling between adjacent DR elements. Dipole-Dipole – coupling between adjacent dipole elements. DR-Dipole – coupling between adjacent DR and dipole elements.

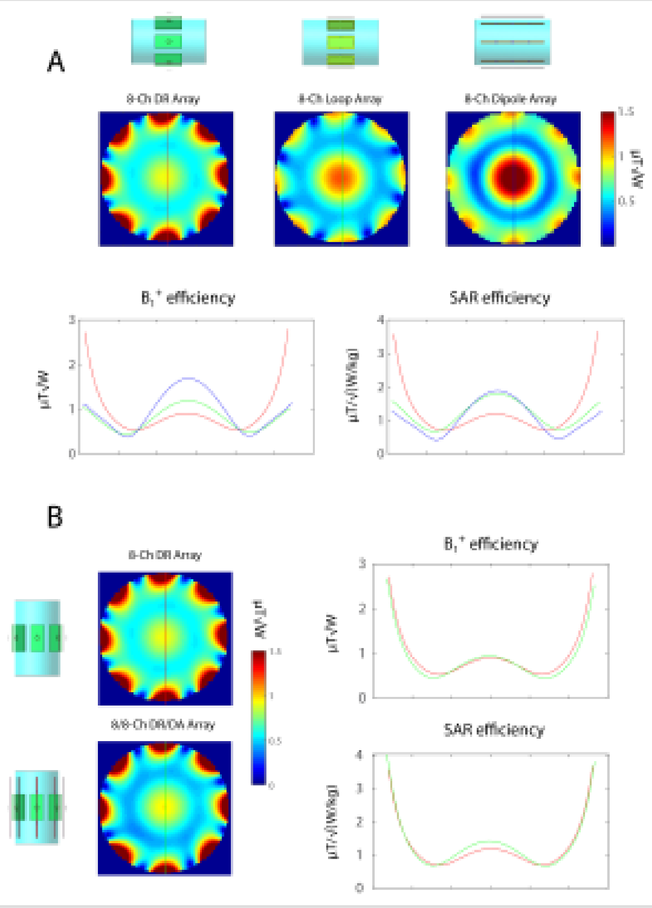

Figure 3: (A) Transmit field and SAR efficiency simulations: 8/8-channel DR-DA array (TX-DR) outperforms 8-ch loop array in surface regions. 8-channel DA array provides the highest B_1^+ and SAR efficiency in the center of the phantom. (B) Using extra DA elements in the 8/8-channel DR-DA array (TX-DR) does not lead to any performance degradation with respect to 8-channel DR array.

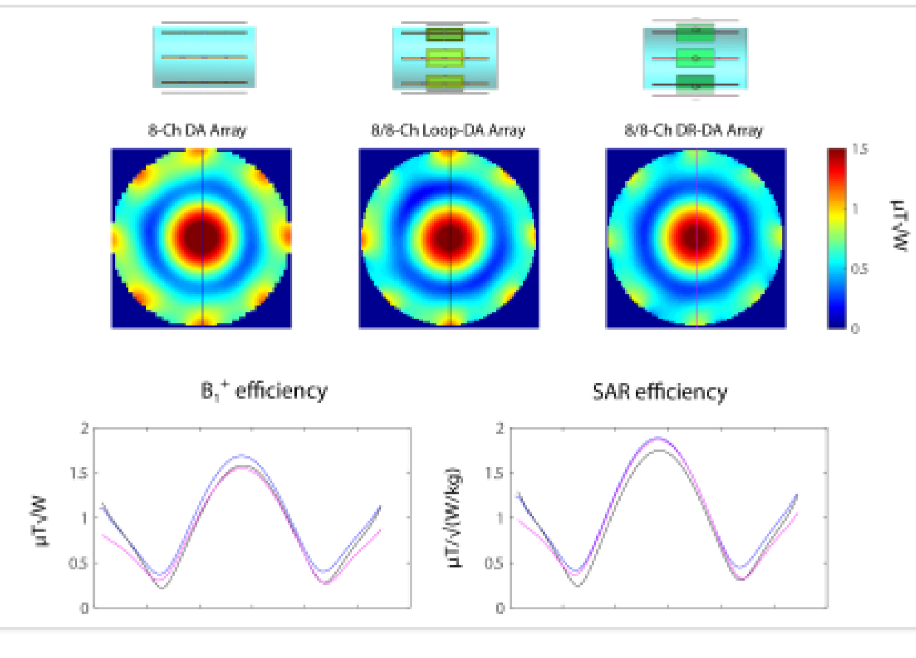

Figure 4: Transmit field and SAR efficiency simulations: 8/8-channel DR-DA array (DA-TX) provides 8% lower B_1^+ efficiency than 8-channel DA array, and only 2% lower B_1^+ efficiency than 8/8-channel loop-DA array (only DA-elements TX active).

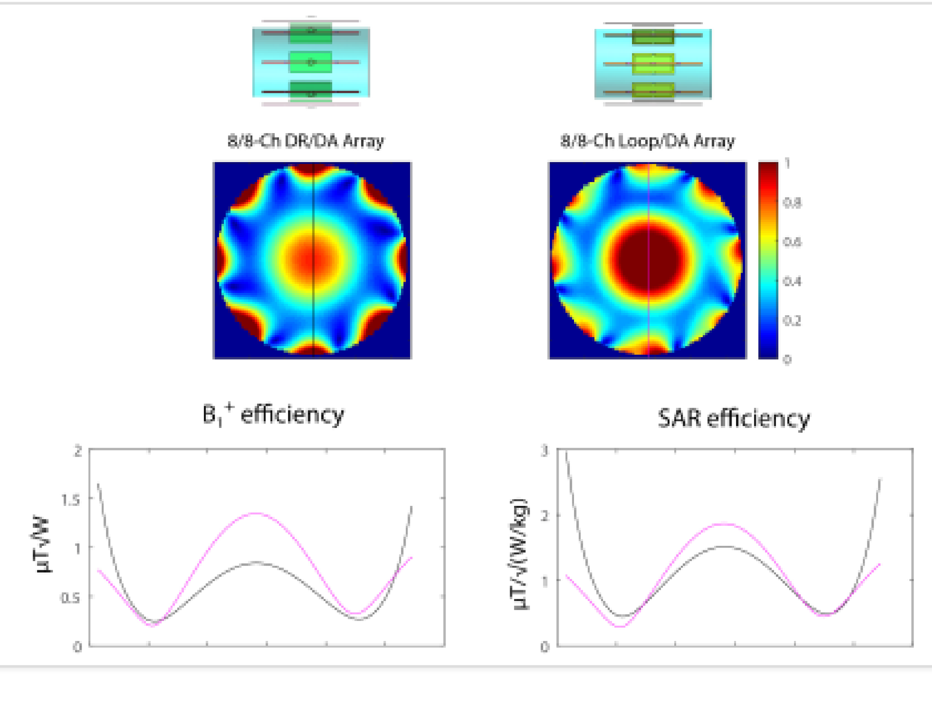

Figure 5: Comparison of 8/8-channel DR/DA array and 8/8-channel loop/DA array. Very high DR dielectric permittivity (ε_r = 1070) results in higher magnetic field concentration in surface regions. Loop elements contribute to the higher transmit efficiency in the center.