Dielectric Enhanced Dipoles for MRI - Approaching the Ideal Current Pattern

W. M. Brink* J. Paška† J. Dai* J. H. F. van Gemert‡ G. Chen†
G. C. Wiggins† R. F. Remis‡ C. M. Collins† A. G. Webb*

Abstract — **In this work we present a systematic evaluation of the potential of combining dielectric materials with an array of electric dipoles for MRI. Design parameters include the permittivity and length of a dielectric sleeve, as well as the dipole length and position of the tuning inductors. Results show that the combined approach improves transmit efficiency and SNR by ∼10 to 15 % compared to an optimized dipole array without dielectric sleeve. The resulting induced current densities reflect an improved correspondence with the ideal current pattern, which explains the gains in performance.**

1 INTRODUCTION

Ever since its introduction in the late 1970s, there has been a continuous effort to operate magnetic resonance imaging (MRI) systems at a higher static magnetic field (B_0) strength, which holds the prospect of increasing the intrinsic signal-to-noise ratio (SNR) available [1]. The increased Larmor frequency involved however also leads to significant changes in the nature of the radiofrequency (RF) fields used for signal transmission and reception, such as a departure from near–field dominance towards including far–field properties such as wave interferences and increased electric field strengths [2]. These changes have also shown to offset the optimality of conventional loop and birdcage designs [3], motivating the pursuit on finding the "best" RF coil design for high field MRI [4, 5].

One of the measures to compare RF coil designs against is the concept of ultimate intrinsic SNR, which forms an upper limit to RF coil performance as dictated by sample properties and Maxwell"s equations [6]. Recent studies using analytical electrodynamic models have shown that the ideal current pattern which achieves the ultimate intrinsic SNR in the center of a cylindrical sample is dominated by distributed longitudinal currents, suggesting that electric dipole elements are the best candidate RF coil element for high field MRI [7].

The difficulty in realizing such a distributed current pattern is however that traditional coil designs using copper conductors can only contribute to the current pattern at discrete locations. The electrodynamics that describe the ultimate intrinsic SNR however do not differentiate the *origin* of these electrical currents, either being generated *actively* by means of active sources, or *passively* via induction within dielectric materials. The effects of dielectric materials between the coil and the sample have been shown to reduce E-field penetration into the sample, reducing the noise sensitivity and improving SNR [8]. Although dielectric materials have been integrated in electric dipole designs before [4], a thorough optimization of the relevant degrees of freedom has not been shown to date.

The aim of this work is to evaluate the potential of combining a dielectric sleeve with an array of electric dipole elements. The design of the dielectric and the dipoles array are optimized, and compared to an optimized dipole array without dielectric. Finally, we compare the current densities induced in the sleeve with the ideal current pattern, as a mechanism that may explain these gains.

2 METHODS

2.1 Dipole and dielectric optimization

An eight-channel dipole array surrounding a cylindrical sample ($\varepsilon_\mathrm{r} = 50, \sigma = 0.5\ S/m$) was optimized in a parametric manner with a dielectric sleeve positioned at the center of the configuration. The cylindrical sample was 20 cm in diameter and 40 cm in length, and the array had a diameter of 25 cm. All simulations were performed using XFdtd 7.5 (Remcom inc., State College, PA, USA) using an uniform 5–mm grid and all postprocessing was performed in MATLAB (MathWorks, Natick, Massachusetts, USA). The evaluation metrics were defined as central transmit efficiency, i.e. B_1^+ per square root of input power, central specific absorption rate (SAR) efficiency, i.e. B_1^+ per square root of peak 10 g averaged SAR, as well as central SNR.

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*C.J. Gorter Center for High Field MRI, Radiology, Leiden University Medical Center, Albinusdreef 2, 2333 ZA Leiden, The Netherlands. Corresponding author e-mail: `a.webb@lumc.nl`, tel.: 31 71 526 5483, fax: +31 71 584 8256.

†Center for Biomedical Imaging, Department of Radiology, NYU School of Medicine, 660 First Avenue New York, NY 10016, New York, USA.

‡Circuits and Systems Group, Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands.

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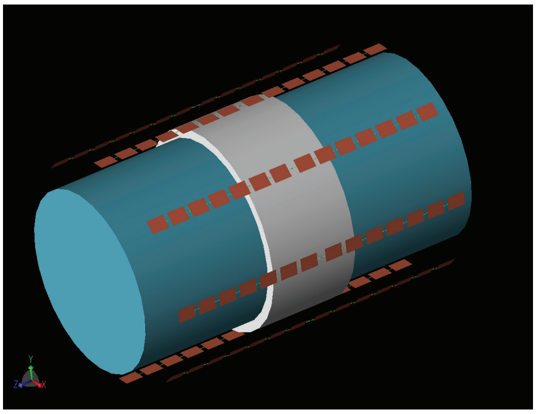

Figure 1: Illustration of the simulation setup. The eight-channel dipole array is partitioned into segments to facilitate optimization of the dipole length and inductor position via circuit co–simulation, resulting in a 104-port model. The dielectric sleeve (shown in white) is varied in dielectric properties and length.

The dipole array elements were modeled using a circuit co–simulation approach by segmenting a 35 cm long and 1 cm wide dipole into sections of 2.5 cm length. This setup is illustrated in Figure 1. The interconnected sections were then combined at the circuit-level using a topological arrangement of open and short circuits and one tuning inductor per leg of the dipole [9]. After tuning the dipoles, a lattice balun matching circuit was incorporated to match the elements to 50 Ω. All reactances were set to have a Q-factor of 150.

A dielectric sleeve of 1 cm thickness was varied in length from 5 cm up to 20 cm in steps of 5 cm, and was varied in relative permittivity from 50 up to 300 in steps of 50. The electrical conductivity of the sleeve was set to 0.2 S/m. The degrees of freedom for the dipole design were evaluated for each of the sleeve designs, rendering a rigorous optimization approach to find the best combined design.

2.2 Ideal current pattern

The ideal current pattern was computed from the fields generated by a circularly polarized transverse magnetic source in the center of the cylindrical sample, which corresponds to a nuclear spin precessing at the Larmor frequency. For objects of large electrical size it has been shown that the resulting tangential electric field component at the surface of the sample corresponds to the ideal current pattern, which can be explained as maximizing the signal sensitivity via reciprocity [8]. The ideal current pattern was then compared to the currents induced in the dielectric sleeve, both with and without the sleeve in place.

3 RESULTS

The variation in maximum attainable central transmit efficiency, SNR and SAR efficiency with the design of the dielectric sleeve are shown in Figure 2. We note that the dipole elements are optimized for each sleeve design and performance metric separately. A smooth optimum can be observed around a sleeve length of 10 cm with a relative permittivity of 200.

With these optimized dielectric sleeve parameters, the variation of the array performance with dipole length and inductor position is shown in Figure 2. A 14% gain in central transmit efficiency and 9% gain in central SNR can be realized when the dielectric sleeve is introduced, and central SAR efficiency is increased by 12%. The corresponding sensitivity maps in the optimized dipole arrays with dielectric sleeve are shown in Figure 5.

Finally, the SNR optimized configuration is compared against the ideal current pattern, the results of which are shown in Figure 5. The mean values along the azimuthal direction indicate that the sleeve increases the current density around the center of the configuration, which is the most dominant contribution as indicated by the ideal current pattern.

4 CONCLUSION

This study shows that the performance of electric dipole arrays for high field MRI can improve when a suitably designed dielectric material is included. The applied current distribution is enhanced in the center due to the sleeve, which improves agreement with the ideal current pattern and explains these performance gains.

Acknowledgments

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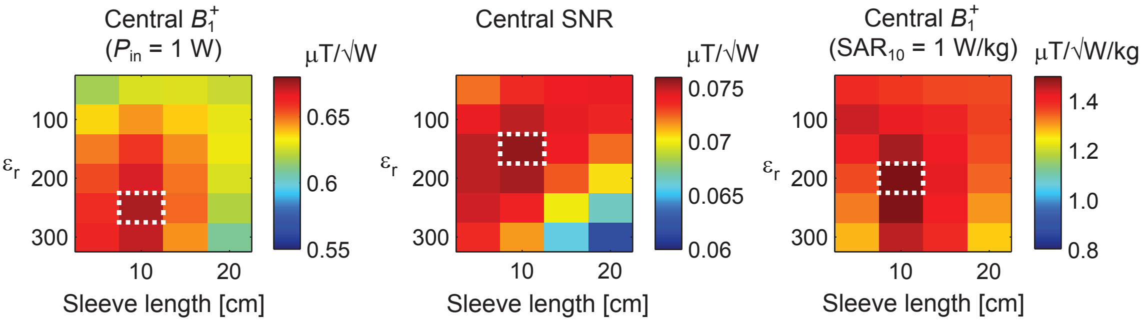

Figure 2: Variation of the maximum array performance with dielectric sleeve properties. For each sleeve design, the maximum attainable transmit efficiency (left), SNR (middle) and SAR efficiency (right) are shown. The optimum dielectric sleeve realizations are encircled in white.

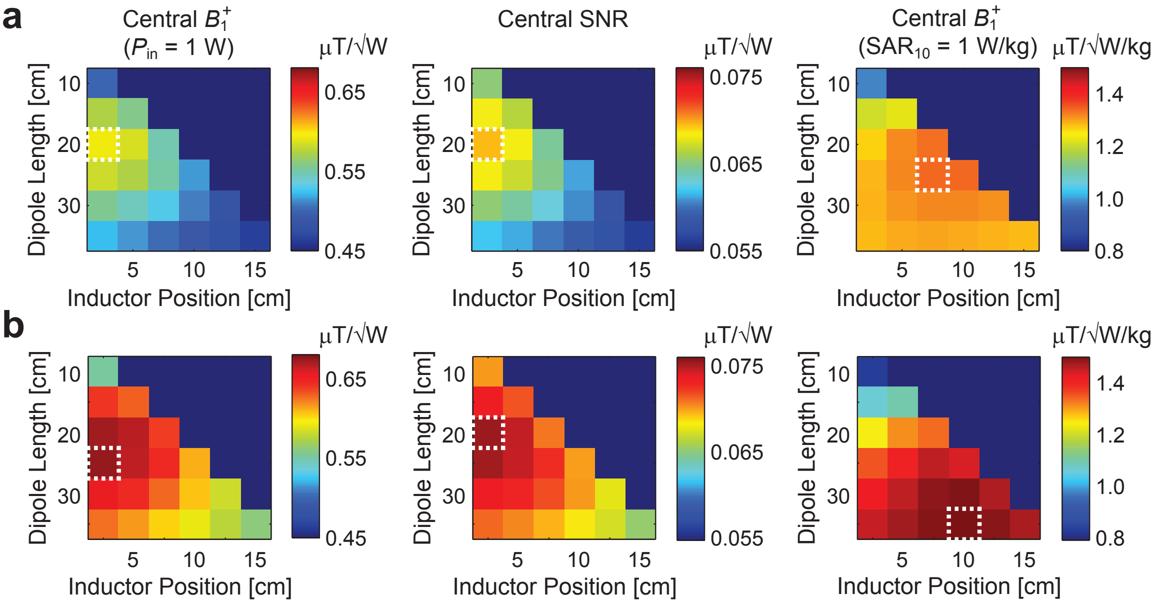

Figure 3: Variation of the array performance with dipole design parameters, without (**a**) and with (**b**) the dielectric sleeve. Optima are encircled in white. Gains of ~10–15% are observed in all performance metrics when introducing the dielectric sleeve, although the trade off between SAR and SNR is increased.

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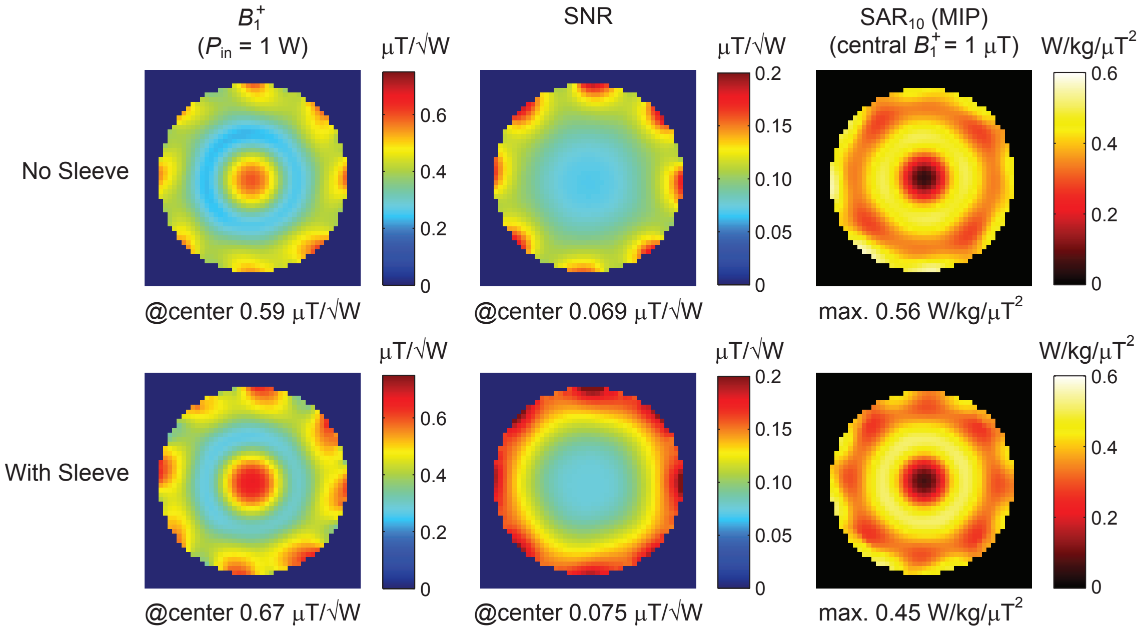

Figure 4: Transverse sensitivity maps and maximum intensity projections (MIP) of SAR_{10} in the optimized configurations as encircled in Figures 2 and 3.

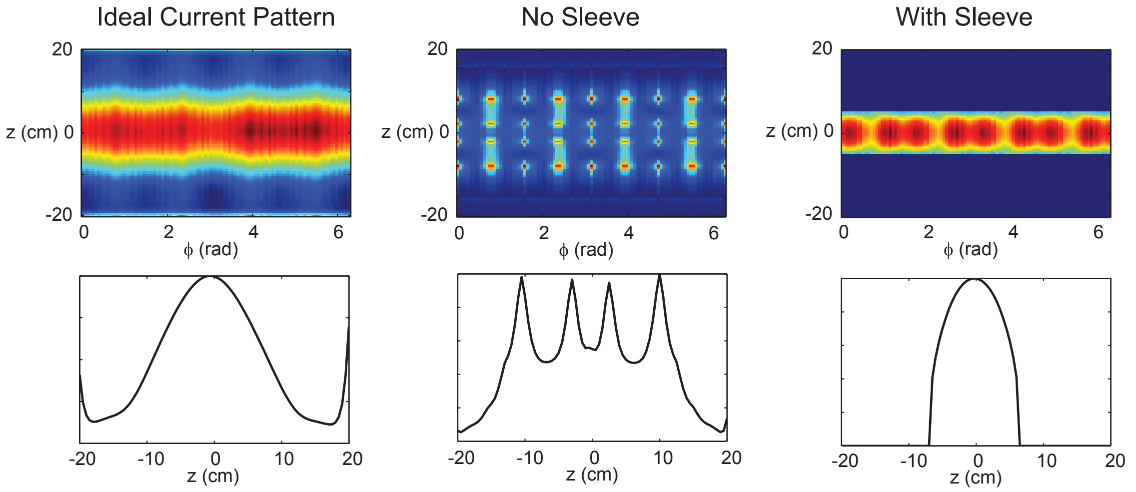

Figure 5: Comparison against the ideal current pattern. Shown are normalized projections along the cylindrical surface (top) and mean amplitudes along the circumference (bottom). The ideal current pattern (left) shows a stronger similarity with the dipole array when integrated with the sleeve (right) than without (center).

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