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Evaluation of Common RF Coil Setups for MR Imaging at Ultrahigh Magnetic Field: A Numerical Study

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Abstract

This study is an evaluation of the ratio of electric field to magnetic field (E/B_1), specific absorption rate (SAR) and signal-to-noise ratio (SNR) generated by three different RF transceiver coil setups: surface coil, surface coil with shielding, and microstrip using a finite discrete time domain (FDTD) simulation in the presence of a head phantom. One of our main focuses in this study is to better understand coil designs that would improve patient safety at high fields by studying a coil type that may potentially minimize SAR while examining potential changes in SNR. In the presence of a human head load, the microstrip's E/B_1 ratio was on average smallest while its SAR was also on average smallest of the three setups, suggesting the microstrip may be a better RF coil choice for MRI concerning patient safety and parallel excitation applications than the other two coils. In addition, the study suggests that the microstrip also has a higher SNR compared with the other two coils demonstrating the possibility that the microstrip could lead to higher quality MRI images.

Keywords

High field; microstrip; specific absorption rate (SAR); signal-to-noise ratio (SNR); RF coil; numerical modeling; electromagnetic calculation

1. Introduction

In the magnetic resonance imaging (MRI), a static B_0 field is present while a varying B_1 field is generated by an RF transmitter coil. In human proton MR imaging, hydrogen nuclei rotating at a precessional frequency (Larmor frequency) due to B_0 will be excited by the B_1

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field and decay, radiating this energy (MR signal) which will be detected by a receiver RF coil. The differing relaxation times of the protons in different tissues are detected by the receiver coil to provide the raw frequency data for imaging with the desired soft tissue contrast [1-5].

There is no known method of generating a B_1 field required for MRI without producing an electric field, due to Maxwell's equations. This electric field generates large amounts of heat in conductive biological samples, which may pose a safety concern for the patient being scanned. The square of the electric field magnitude is directly proportional to SAR (Specific Absorption Rate) [6], and a safe maximum exposure to the RF electromagnetic field is regulated by the FDA. In addition, in the recently introduced parallel excitation method, a promising technology for fast selective excitation and B_1 shimming, the acceleration rate is also proportional to the electric field magnitude. A RF coil array with minimal electric field in the region of interest would be desired and essential for parallel excitation applications in practice.

This study is an evaluation focused on the ratio of electric field to magnetic field (E/B_1), Specific Absorption Rate (SAR) across the planes of three commonly-used RF transceiver coil setups in high field MRI in-vivo: surface coil [7-8], surface coil with shielding [9], and microstrip coil [10-14]. The study also performs numerical evaluation to acquire signal-to-noise (SNR) measurements of these three coils that are consistent with a previous experimental study of SNR comparison of the setups [10]. Each of the coil setups were LC or transmission line resonators with adjustable capacitor values to set their resonance frequencies at 300 MHz, the proton Larmor frequency at 7T. The use of E/B_1 ratio, rather than E field, is more proper in MR performance evaluation because MR experiments require radio frequency B_1 fields, and this E/B ratio represents a normalized electric field value [15]. A comparison study was performed amongst these three common RF Coil setups using a finite discrete time domain (FDTD) [16-17] simulation with a human head phantom. In addition, simulations were used to acquire and compare SAR values, which cannot be conveniently performed non-invasively in MR imaging experiments [18].

In addition to helping improve the safety of the patient through studying the SAR issue, we hope also to consider improved setups that would help to attain better parallel excitation performance [19-20]. In addition, R, the factor by which the spin excitation time is reduced, is proportional to the magnitude of the electric field, while SAR is proportional to the electric field squared [21-23]. Thus a higher reduction factor causes the SAR involved with the coils to increase. By determining an optimal coil setup that will create a smaller electric field, this will enable users to use higher reduction factors for parallel transmit excitation while still remaining below the FDA limits for radiofrequency exposure, decreasing scan time and improving SNR [13, 24-27].

Such results from this study may yield information for better understanding of heating issues which may lead to revelations in MRI safety issues and parallel excitation performance.

2. Methods

2.1 Finite- difference time domain method

To perform our study, we used the finite-difference time-domain method (FDTD) [16], an electrodynamics modeling algorithm that may be carried out using the commercially available xFDTD software (Remcom, Inc., State College, PA).

In the simulation, we established numerical models for three different coil setups: a regular surface coil, surface coil with shielding, and a microstrip surface coil with a Teflon dielectric (permittivity $\epsilon=2.1$). A break was made in the conductors of each coil, capacitors were added across the gaps of the coils to create the LC circuit configuration that enables the setup to function as a resonator. A human head phantom was placed with its edge approximately 1 cm away from the center of the coil. The human head phantom was 18 centimeters in diameter with a conductance value of 0.553 S/m, relative permittivity of 51.898, density of 1050 kg/m³, and its edge was placed 1 cm away from the coil.

2.2 Coil setups

We maintained the conductor strip widths of each coil at 6 mm, the diameter of the coils at 8 cm, and using a Gaussian waveform pulse, adjusted the capacitor values to set their resonance frequency at 300 MHz (<5% accuracy)—proton Larmor frequency at 7T. The surface coil included a 1.09 pF capacitor, the surface coil and shielding were placed 5 centimeters apart with a 1.10 pF capacitor, and finally, the microstrip with a Teflon ($\epsilon=2.1$) dielectric contained a pair of 3.35 pF termination capacitors at each end (Fig. 1a-c). Prior to comparison between the three coils, two properties, the physical dimensions of the coils and capacitor values, were already adjusted to optimal performance with several simulation runs to minimize their E/B₁ ratios. This optimization was done with the presence of a human head phantom with its edge placed 1 cm away from the coil (Fig. 1d-f). A 300 MHz sinusoidal pulse was then applied to each of the three different coil setups and the steady state electromagnetic field results were logged accordingly. E/B₁ ratio measurements were then taken for each of the three coils. Specifically, the average of the E/B₁ ratio across each plane parallel to the coil face was plotted with respect to distance away from the center of the coil using Matlab software. In addition, the color maps for planes 2 cm, 5 cm, and 8 cm were also plotted for comparison of the spatial distribution of the E/B₁ ratio magnitudes.

2.3 Post Processing Results

We wrote a program using Matlab (Mathworks) to analyze our data matrices, for computing and plotting the electric field to magnetic field ratio colormaps as well as plotting the E/B₁ ratio average for each plane as a function of distance away from the center of the coil. In addition, we acquired colormaps indicating the spatial distribution of normalized SAR relative to B₁, across an 18 cm by 18 cm field of view (FOV) for various planes at distances 2 cm, 5 cm, and 8 cm away from the center of the coil. A graph indicating the average SAR value across each plane versus distance was also plotted for comparison between the three RF Coil setups.

In addition to the normalized SAR and E/B ratio, we also computed the signal-to-noise ratio of the three setups through observing previously used SNR equations [28-29]. While observing these equations in addition to using the B field data acquired through xFDTD, we plotted the average SNR of each plane as a function of distance for each of the three coil setups and compared them accordingly.

Thus, we are able to compare the graphs of the E/B₁ versus distance and SAR versus distance plots of the three RF coil setups as well as use the color-maps to see whether or not a particular setup will produce smaller E/B₁ and SAR intensity compared with the others. The signal-to-noise ratios were also calculated with the phantom present.

3. Results and Discussions

Thus in the presence of a human phantom head, after the E/B₁ ratio and SAR values were calculated, it was found that the microstrip displayed the smallest E/B₁ ratio and SAR average values across a 12 cm by 12 cm plane as compared with the other two common coil setups (Fig 2, Table 1). Near the coil, the microstrip's average E/B₁ ratio is substantially smaller than the shielded surface coil by 3×10^7 V/m/T. As the distance away from the coil increases, the E/B₁ ratios of the three curves grow closer to one another in value past 4.5 cm away from the coil. The microstrip surface coil exhibited an increasing E/B ratio from the center of the coil to approximately 1.2 centimeters away, whereas both the surface coil and shielded RF coil setups displayed decreasing E/B ratio values across the whole plot.

With the loaded human head phantom, the microstrip configuration displayed the smallest E/B₁ ratio followed by the coil with shielding configuration, and lastly, the regular surface coil. During the comparison of SAR values for the three configurations, the microstrip had the smallest average value across the plane for distances starting from one centimeter away from the coil. This was done because the human head phantom was placed with its edge one centimeter away from the center of the coil. This ordering of the dominating coils with respect to average E/B₁ ratio values did not change for the remainder of the distance calculated away from the coil. Color-maps of the individual planes parallel to the coil face confirm the microstrip's smaller E/B₁ ratio (Fig. 3) and SAR (Fig. 4) in magnitude and area for distances 2 cm and 5 cm away. At 2 cm away, the microstrip contained a decreased area of E/B values higher than 2.1×10^8 V/m/T in comparison with the color-maps of the other coil setups. At 5 cm away, the microstrip remained below 1.02×10^8 V/m/T while the other coil setups exceeded this value with the surface coil setups reaching as high as 1.4×10^8 V/m/T in certain regions of the plane.

The SAR colormaps exhibited similar behavior with the microstrip compared with 0.55 and 0.32 for the SNR of the shielded RF coil and regular surface coil respectively (Fig. 5). At 5 cm away from the coil, the microstrip maintained its lead as having the largest SNR with a value of approximately 0.28 while the shielded surface coil and regular surface coil had SNR values of 0.22 and 0.17 respectively. Moving further from the center of the coil, the distinction between the SNR of the three coils decreased.

The data acquired from these experiments suggested that with the microstrip setup with the human head model loaded in would yield both a smaller E/B_1 ratio and a lower SAR as compared with the exhibiting a 25-30% smaller area of SAR values higher than 1.2×10^{13} W/kg/T 2 cm away from the coil. For SAR color-maps 5 cm away from the coils, the SAR values of the microstrip remained below 7.4×10^{12} W/kg/T whereas the surface coil reached an SAR of up to 1.02×10^{13} W/kg/T generated. There was less of a distinction in the color-maps for a distance of 8 cm away from the coil. However, it may be noted that 8 cm is quite far from the center of the coil. Despite this, it can be possible to suggest that such E/B_1 ratio and SAR findings support the microstrip as a better setup choice compared with the other two configurations concerning patient safety and efficiency of parallel excitation.

In addition to the E/B_1 ratio and SAR calculations, we also evaluated the signal-to-noise ratio (SNR) of the various surface coils. After inputting the simulation results into a written Matlab program, it was found that the signal-to-noise ratio of the microstrip was higher in value as compared with the other two setups. At 1 cm away from the coil, the microstrip displayed an SNR of 0.6 as shielded RF coil and surface coil. From the Matlab plots, this has been shown to be a trend present across the complete plotted distances.

When measuring the signal-to-noise ratio of the surface coil, it was unsurprising that the shielded surface coil had a higher SNR relative to the regular surface coil, since the shielding would help prevent radiation loss, allowing a higher B_1 field to be utilized in our MRI scan and thus higher SNR. In addition, with the current E/B_1 plots, it also made sense that the SNR of the microstrip was higher than both the surface coil and shielded RF coil case since a lower E/B_1 and SAR indicates a higher B_1 field generated for a given electric field, which should yield better MR signal. Near the coil at merely 1 cm away from the center of the coil, the microstrip outperformed the shielded surface coil by approximately 9% while displaying an improvement of the surface coil by 87%. At approximately 2.8 cm away from the center of the coil, the microstrip SNR reached its largest percentage lead and outperformed the runner-up shielded coil by approximately 22% and the surface coil by 63%.

Electromagnetic fields and SAR of three types of commonly used coils or elements in arrays were numerically studied at the ultrahigh magnetic field of 7T. This study suggests the given our size parameters, microstrip design is a better choice over surface coil and surface coil with shielding in terms of MR safety at ultrahigh fields and additionally, provides an increase in the SNR of the MR signal. While these results are from study of a single coil, we believe that these benefits could be extended multiple coil designs and provide guidance in designing transmit arrays for parallel excitation applications. In parallel excitation, the acceleration rate is proportional to the magnitude of the electric field of the RF coils. Thus, transceiver arrays consisting of elements with lower E/B_1 should help to improve the efficiency of parallel excitations.

Future experiments may further lead us to understand the most ideal coil setup for MR imaging. Through the maximization of the B field, and the minimization of the E field, it is possible that not only will greater safety be achieved with smaller SAR, but potentially other features of the MRI experiments such as parallel exciting performance, quality factor, and

signal-to-noise ratio may improve, leading to more efficient and accurate MRI scans at high fields.

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Figure 1.

(a) Surface Coil configuration. Capacitance value: 1.09 pF (b) Surface Coil and shielding configuration. Coil placed 5 centimeters from shielding. Capacitance value: 1.10 pF (c) Microstrip Configuration. Thickness= 5mm. Teflon width= 2.6 cm. Pair of capacitors each at: 3.35 pF. (d-f) Actual setup configuration including the human head phantom approximately 18 centimeters in diameter with a conductance value of 0.553 S/m, relative permittivity of 51.898, density of 1050 kg/m^3 , and its edge placed 1 cm away from the coil. The coils consist of a loop conductor that is 8 cm in diameter with a width of 6 mm.

Figure 2.

(a) Average E/B_1 ratio (normalized E field units: V/m) of a plane parallel to the coil face versus distance from the 8 cm diameter coil face w/ phantom. The knee one centimeter from the center of the coil is due to the fact that the phantom is one centimeter from the center of the coil. (b) SAR versus distance from coil. Curves included for surface coil, surface coil w/ shielding with 5 cm between conductor and shielding, and microstrip with 5 mm thick Teflon insulator.

Figure 3.

Colormaps indicating the magnitudes of the E/B_1 ratio across a plane with a phantom (FOV: $18\text{ cm} \times 18\text{ cm}$) parallel to and at a distance 2 cm (a-c), 5 cm (d-f), and 8 cm (g-i) away from the center of the coil for the surface coil, shielded coil with 5 cm distance between conductor and shielding, and 5 cm thick microstrip respectively.

Figure 4.

Colormaps indicating the magnitudes of the SAR across a plane with a phantom (FOV: 18 cm × 18 cm) parallel to and at a distance 2 cm (a-c), 5 cm (d-f), and 8 cm (g-i) away from the center of the coil for the surface coil, shielded coil with 5 cm distance between conductor and shielding, and 5 cm thick microstrip respectively.

Figure 5. Average signal-to-noise ratio (SNR) versus distance from the coil with a loaded phantom. Curves included for surface coil, shielded coil with 5 cm distance between conductor and shielding, and 5 cm thick microstrip.

Table 1

The weighted average E/B ratio across the planes (FOV 12cm × 12 cm) at distances 2 cm, 5 cm, and 8 cm away with the phantom load. Across these three planes, microstrip of 5 cm insulator thickness has the highest E/B ratio, shielded coil with 5 cm distance between conductor and shielding has the second highest, while the surface coil has the lowest average.

Distance	Surface Coil	Coil w/ shielding (shield distance 5 cm)	Microstrip Coil (Height=0.05mm)
2 cm	1.158E+08	1.107E+08	1.031E+08
5 cm	4.194E+07	4.183E+07	4.139E+07
8 cm	3.806E+07	3.767E+07	3.702E+07
Ave Over 8 cm	8.165E+07	7.949E+07	7.378E+07