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Effects of Receive-Only Inserts on SAR, B_1^+ Field and Tx Coil Performance

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Abstract

Purpose—To evaluate the effect of different cylindrical and close conforming receive only array designs on spin excitation and specific absorption rate (SAR) of a 7 Tesla transmit only head coil.

Materials and Methods—We developed FDTD models of different receive only array geometries. Cylindrical and close fitting helmet arrays with varying copper trace widths; a TEM Tx coil model and two head models were used in numerical simulations. Tx coil coupling was experimentally measured and validated with FDTD modeling.

Results—Changing copper trace width of loops in array models caused subtle changes in RF absorption (<5%). Changes in SAR distribution were observed in the head models with Rx-only inserts. Peak SAR increased (–1 to +15%) in different tissues for a mean B_1^+ in the brain of 2 μ T. Total absorption in the head models for 1 Watt forward power increased (5 to 21%) in the heads with Rx-only inserts. Changes in RF absorption with different Rx-inserts indicate a change in RF radiation of the Tx coil even when changes in B_1^+ and coupling between ports of Tx coil were minimal.

Conclusion—Changes in local/global SAR and subtle changes in B_1^+ field distributions were observed with the presence of Rx-only inserts. Thus, incorporation of the receive-only array effects are needed when evaluating SAR and designing RF transmit pulse waveform parameters for shimming and/or Tx-SENSE for 7 T MRI.

Keywords

RECEIVE ARRAYS; B_1 FIELD AND SAR; RF MODELING

Introduction

Parallel transmit and receive systems have been built for high and ultrahigh field MRI. Dedicated transmit and receive systems have been designed to handle the challenges that

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arise at high frequencies when the sample becomes electrically large compared to the operating wavelength. RF inhomogeneity is handled by designing better transmit-only arrays and shaping transmit wave forms (shimming) to obtain homogenous spin excitation at low RF absorption. Close fitting decoupled receive-only arrays have been built to increase the signal to noise ratio (SNR) and acceleration in acquiring MR images. Although highly sensitive, multichannel receive-only arrays for high field MRI have been built. There are few studies that look at the influence of close conforming receive-only arrays on transmit coil performance, thus assuring the combination of Tx and Rx arrays are safe to use.

Static fields up to 8T have been shown to have no serious health effects. Several studies by (1, 2) on gradient coils and of movement in high fields have been done as part of safety assurances of MR systems. The Food and Drug Administration (FDA) and International Electro-technical Commission (IEC) have guidelines regarding evaluation of multi-channel Tx/Rx systems. Prior work on safety assurance of multimodal electroencephalography and functional imaging (EEG-fMRI) have shown currents induced on closely conforming leads/electrodes cause increased radiofrequency (RF) absorption (3, 4). An earlier study done on a phantom at 3 Tesla showed SAR increased in the phantom with the presence of two Rx-loops (5). In this study, numerical simulations and experiments are used to look at the effect of a wide variety of receive-only insert designs such as cylindrical and close fitting helmet arrays and their effect on the transmit RF field. " B_1^+ field" or the transmit spin excitation, and RF absorption or specific absorption rate (SAR), of different receive array geometry for the transverse electromagnetic (TEM) coil are summarized.

Higher spatial resolution, contrast, and high SNR at ultrahigh field strengths draw on the stringent requirements of transmit and receive arrays. The requirements of transmit and receive chains, though interconnected by the reciprocity law of electromagnetics (6, 7), serve very different roles, thus the use of dedicated Tx and Rx arrays have become a common design paradigm in MRI. Transmit arrays are required to produce homogenous spin excitation at low RF absorption levels. A highly decoupled set of independent observers are best suited to recover a signal corrupted by noise. Thus, one goes to great lengths to ensure that the parallel observers are isolated in the receive array using overlaps to cancel mutual inductance and preamplifier based decoupling (8).

Traditionally receive loop arrays were built with 4-5 mm wide copper tape or flexible printed circuit material. With an increasing number of receive channels from 16, 32, to 96 channels, using copper tape meant significant surface area of the human head was covered with copper possibly resulting in higher transmit voltages. Current designs of loop arrays for ultra-high fields use 16-18 American wire gauge (AWG) tinned wire to minimize copper coverage. Despite difficulties in constructing and modifying loop arrays using tinned wire (modifying overlaps and difficulties in building matching circuits), arrays built with wires can reduce the transmit voltage required by 24 percent when compared with copper tape (9).

The specific absorption rate (in W/Kg) given by:

$$SAR_{(i,j,k)} = \frac{1}{2} \frac{\sigma(i,j,k) (E_{x(i,j,k)}^2 + E_{y(i,j,k)}^2 + E_{z(i,j,k)}^2)}{\rho(i,j,k)} \quad (1)$$

is a function of sample size (m), geometry of coil/design, MR frequency, RF pulse duration (τ) and its amplitude repetition time (TR), tissue conductivity (σ), dielectric constant and density (ρ) and other parameters(10). The whole body absorption and σ radiation from a transmit coil during a MRI scan can be obtained accurately by measuring (1) the output power from RF amplifier, (2) measuring cable loss to the transmit coil and (3) measuring reflection at the transmit coil ports with the subject. The fraction of incident forward power is $(1 - \text{reflection}^2)$. Whole body absorption can be accurately obtained from incident power and radiation pattern of the Tx coil. Local SARs are generally determined using numerical simulations. RF hot-spots are created due to uneven distribution of RF power in association with restrictive conductive patterns to flow (11). Hot-spot ratios (peak SAR/mean SAR) > 20 have been reported even at 3 Tesla (12). Manufacturers and system designers must meet the regulatory stipulations of SAR averaged over 10 gram of tissue, even if actual temperature rise due to hot-spots is dependent on several factors such as heat dissipation, perfusion, heat transfer to surrounding, metabolism etc.

Materials and Methods

Finite difference time domain (FDTD) models of different receive only array geometries such as cylindrical and close fitting helmet arrays with varying copper trace widths were developed for the full wave simulations. An eight element TEM resonator and its FDTD model were tuned and matched to a human head and an anatomically detailed model at 300 MHz by adjusting the gap between the inner coaxial elements. Measurements of reflection and coupling between ports were validated to match results obtained from numerical simulations. Two anatomically detailed head models were used. The TEM coil model was individually tuned to the different heads. B_1^+ and SAR distributions were obtained for the two head models. When different Rx-only inserts were introduced, resonant frequency changes for the source ports of TEM coil were minimal (< 3 MHz). The TEM coil voltage was scaled for equal transmission for the different cases (two heads and different Rx-only array geometry). B_1^+ and SAR distributions were obtained for the two head models with the different RX-only array geometry. Changes in RF absorption per 2 μT in brain; and B_1^+ field distribution in brain per 1 Watt absorption and for 1 Watt forward power are summarized for the different copper trace widths and Rx-only geometries.

Modeling

Finite difference time domain (FDTD) models of the TEM transmit coil (Figure 1) and different receive-only inserts (Figure 2) used in full wave simulations at 7T are shown. A three dimensional grid with spatial resolution 1.6 mm ($< \lambda / 20$) and temporal resolution of ($\Delta t = 3e^{-12}$) was used for simulation as per Courants stability criterion (13). The computational domain was terminated using 32 layers of perfectly matched layer (PML) with electric and magnetic losses as per Berenger (14) to minimize reflections from the end of the domain. The computational domain was constructed by setting the RF properties of

the Yee cell to conductivity (σ) and dielectric constant (ϵ_r) to values corresponding to tissue (one of 22 or 19 types), air, Copper, or Teflon. Two head models model 1 of 19 tissues and 3.6 Kg and model 2 of 22 tissues and 4.7 Kg were used in the simulations. Model 2 was 30% larger than model 1 in terms of volume. The RF shield, inner and outer coaxial copper, and receive array loops were modeled as perfect electric conductor (PEC), with the tangential component of electric field set to zero.

Electric (E) and Magnetic (H) field computations based on Maxwell's differential equations were obtained to second order accurate central difference estimates on the 3D Yee grid, at spatial intervals of $\delta/2$ and temporal intervals of $\Delta t/2$ in a leapfrog manner. The value of a component of E (or H) at any position can be determined from its previous value and the previous values of H (or E) components at adjacent grid positions (15).

Transmit Coil Model and Experimental Measurements

A transverse electromagnetic (TEM) resonator was used for the transmit coil. The transverse electromagnetic resonator coil is made of 8 coaxial resonators located 45 degrees apart between two circular rings (9' internal and 13' external diameter). The resonator is encased in an outer RF shield to improve RF efficiency. This distributed coaxial resonator is robust, and efficient when compared to lumped element birdcage resonators at high frequencies (16). Four of the eight ports are active sources and were connected in quadrature to produce

circular polarization. Voltage per port was scaled by a factor $\sqrt{1 - S_{xx}^2}$ that is dependent on the reflection (S_{xx}) seen by the port to equalize transmission across ports. Figure 3 shows the validation of match of Scatter Parameters obtained by a network analyzer with those from FDTD simulation. The 8 element TEM resonator and its EM model were tuned and matched to a human head/model respectively at 300 MHz by adjusting the gap between the inner coaxial elements. The measurements of reflection and coupling between ports of the coil are a good match with results obtained from numerical simulations.

B_1^+ maps of TEM coil with and without Rx-only inserts

To evaluate the effect Rx-only inserts have on B_1^+ distribution of TEM resonator coil, a 16 element TEM coil with four active ports connected in quadrature and a 14Ch helmet array were used. A two voltage GRE sequence was used, with image intensity fit with a sinusoid. The B_1^+ map acquisition parameters : TR =10 msec, TR effective=15 sec, TE = 5.2 msec, FOV =22 cm, resolution 64×64, slice thickness 3 mm, receiver bandwidth 510 Hz.

Receive-only Array Models

Cylindrical overlapped 8-loop and staggered 16-loop array geometry conformed to a cylinder of 9 inch diameter and 6 inch height. The close conforming 32-loop array conformed to a prototype helmet, and extracted from CAD models. Geometry of cylindrical Rx-only inserts created using Matlab were based on working designs (17). Rigid body rotation of extracted models from CAD used four reference points, the rotation/translation operator used to create the 32-loop array in the new reference frame was based on least square fitting (18).

We modeled cylindrical and close fitting helmet receiver geometries as they are the most prevalent designs used in MRI. Active and passive detuning of loops in array (two per loop for 16 and 32-loop array and 4 per loop for 8-loop array) were modeled as open circuit. The detuning circuits fragment the copper of the loop array, and protect the preamplifiers during transmission. Modeling them as open circuit was done by cutting the copper of the loop models. Open circuit modeling as well as the inclusion of pointed wires will likely provide higher electric fields intensities than actuality.

To test if copper trace width had any effect on the TEM coil transmit field, copper width of the 8 and 16-loop arrays were varied from 3.2 mm to 6.4 mm.

Results

Scatter Parameters

The TEM coil simulations have been validated to produce excellent match with experimentally obtained transmit and receive field maps (19, 20). Figure 3 shows a successful match in scatter parameters obtained from a network analyzer with those obtained from full wave FDTD simulations. The TEM coil model was tuned to 300 MHz by adjusting inner copper lengths in the model. Shift in resonant frequency with different receive-only inserts was < 3 MHz in numerical simulations. The coupling between adjacent (S_{12}) and opposite (S_{13}) ports for the two head models when different receive-only inserts were used are summarized in Table 1. The reflection of two ports of TEM coil and the changes with different Rx-inserts are also shown. The maximum change in reflection was (<13%). The TEM coil model was not retuned for different Rx-inserts but voltage of each port was scaled for equal transmission. Percent change in coupling was less than 6% for the different cases. Thus, the existing receive-only array designs minimally alter the coupling between ports of the TEM Tx coil.

B_1^+ maps of TEM coil with and without Rx-only inserts

Figure 4 (a&b) shows sagittal and coronal slices of B_1^+ from FDTD simulations on an anatomically detailed head model without and with an 32Ch helmet Rx-only insert. Figure 4 (c&d) shows invivo B_1^+ maps obtained at 7T in a TEM coil without and with a 14Ch Rx-insert conforming to the head. The B_1^+ distribution without and with the Rx-inserts remained similar both qualitatively and quantitatively, thus the Rx-inserts do not degrade the spin-excitation performance of a TEM coil.

Mean B_1^+ field in brain

Figure 5 shows the axial, coronal and sagittal slices of B_1^+ distribution in the two heads for 1 Watt of total absorption. Mean B_1^+ field in the brain per 1 Watt total absorption was computed. As a result, the larger head has effectively lower mean B_1^+ field per 1 Watt of total absorption than the smaller head. The smaller head model 1 has a higher mean B_1^+ than the larger head model 2 (0.76 versus 0.6 μ T). Table 2 summarizes the percent change in B_1^+ field when different receive-only inserts were used for 1 Watt total absorption and 1 Watt forward real power. The changes in mean of B_1^+ in the brain were minimal (< 4%) for total absorption and (<14%) for the same forward real power when different Rx-only array inserts

were used. Thus, while total absorption and B_1^+ increased (as will be discussed in the next section) and radiation decreased with different receive-only inserts; mean B_1^+ field per 1 Watt of absorption had negligible change.

Changes in Global Absorption in Head

Total absorbed power in the head is given by

$$P = \sum \frac{1}{2} \sigma E^2 dV \quad (2)$$

where σ is conductivity of voxel, dV is the voxel volume and E is the average electric field. Table 3 summarizes the changes in total RF absorption when different receive-only inserts were used for a mean B_1^+ of 2 μ T in the brain and for 1 Watt forward power. Total absorption in the head models for the same forward power increased (5 to 21%) with different Rx-only inserts and changed (-10 to +18%) for the allowable peak local of 10W/Kg per 10gm. Conservation of energy indicates Forward Real power = Absorbed power + Radiated power. Thus, for equal forward power an increase in the RF absorption in the head models would imply a decrease in radiation from the TEM coil. Figure 6 shows the Axial, Coronal and Sagittal slices of SAR (Watts/Kg) per 10 gram of tissue in the two head models.

Changes in Global Absorption with Copper Trace Width

Figure 7 shows the change in RF absorption for the same real forward power in the two heads and 9 tissues that constitute 80% of total absorption, when different Rx-only inserts were used. The overall effect of copper trace width on RF absorption was small (<5%). Total absorption increased for the staggered 16-loop array, while it decreased for the 8-loop array.

Changes in SAR: Distribution and Peak Local Intensity

Table 4 summarizes the changes in peak local SAR when different receive-only inserts were used for a mean B_1^+ of 2 μ T in the brain and for 1 Watt forward power. Peak local SAR in the head models increased (19 to 31%) with different Rx-only inserts for the same forward power and changed (-1 to +15%) for the same mean B_1^+ in the brain.

Figure 8 shows sagittal slices in the two head models plotted at the peak local SAR location. The percent change in SAR from the base case without the 8-loop Rx-only insert, and changes in SAR with the presence of 16 and 32 loop Rx inserts are clearly highlighted in the plots. To analyze the regions with an increase in SAR, the percent change plot was overlaid with conductivity of different tissues at 300 MHz. The SAR increased at regions with tissues differing in conductivity. Regions adjoining the sinuses, nasal area, ears, bone-brain interface, and adjoining the eyes show a notable increase in SAR.

Figure 9 shows the changes in peak SAR intensity (averaged over 10 gram of tissue for a mean B_1^+ field in brain of 2 μ T) in the two head models when different receive-only arrays were used. The peak local SAR (hot-spot) location and intensity in some tissues changed when Rx-only inserts were used. The peak SAR shows an overall increase for the 8-loop

array, and in some tissues when using the 32-loop helmet array. The staggered 16-loop array had minimal changes in its peak SAR distribution. The close fitting array caused a surface hot-spot in the skin, while the peak SAR in the rest of the tissues decreased.

Discussion

Effect of Rx-only inserts on SAR

Rx-inserts scatter the Tx RF fields and have been shown to increase local and global SAR in this study. In the 16-loop array local SAR decreased in the brain while increasing outside the brain. Local SAR increased for the 8 and 32-loop configurations. Local SAR changes are sensitive to type of Rx-only inserts, in addition to complex EM interactions at boundaries of different media. SAR changes have been obtained for a mean B_1^+ in the brain and for 1 Watt forward power. Table 3 shows total absorption in the head models increased (5 to 20%) when different Rx-inserts were used for the same forward power. Based on these results, forward power can be used to generally estimate total absorption in the head models with the cylindrical Rx-inserts (compared to an overestimation without Rx only inserts).

Peak local SAR or Hot-spots

The boundary conditions at the interface of two media predict a possible pileup of charges at the interface corresponding to the difference in normal electric field components. The potential difference due to the boundary conditions form the driving potential for RF currents to flow. Different tissues offer varying resistance to flow of current, thus the electric fields and induced RF currents in the tissue determine the hot-spot or peak local SAR locations in the head models.

FDTD estimation of SAR, effect of Truncation of head models

The neck, shoulder, and torso provide boundary conditions for induced currents in the head. (21) have shown peak SAR intensity (<10 %) and location change with truncation, depending on the model used (head+neck, head +neck+shoulder, versus full body). Changes in local SAR with Rx-inserts presented here could vary when the interaction of the whole body/shoulder is considered.

Temperature rise from SAR

Detailed and accurate models of different detuned receive arrays have been shown to affect RF absorption. The actual increase of tissue temperature is dependent on thermoregulatory factors of the body (perfusion, sweating, metabolic rate), and heat loss to surrounding matter through convection and/or conduction.

Mapping between in-vivo temperature raise from SAR is not straightforward. The heat transfer models (perfusion, conduction etc.) make assumptions on subject dependent thermal conductivity and specific heat parameters which could lead to inaccuracies. Thus, Food and Drug Administration (FDA) and International Electro-technical Commission (IEC) have formulated safety statutes based on SAR (which one has to adhere while developing multi-channel Tx/Rx systems). IEC 60601-2-33 stipulates MRI systems must limit locally deposited RF power to not exceed 10 W/Kg per 10 gram of tissue. The global SAR limits

for head and trunk are 3.2 W/Kg and 4 W/Kg (22). Accurate models of the receive-only array must be incorporated in the optimization procedures that determine RF transmit pulse waveform parameters (shimming) when using a transmit array to tackle RF inhomogeneity in B₁⁺ and RF absorption challenges simultaneously for high and ultra-high field MRI (23).

Summary of Results

- Different receive-only inserts do not change coupling of TEM coil (< 6%). Changes in reflection was (<13%)
- Although absorbed power and mean B₁⁺ in the head increased in the presence of receive-only inserts. Mean B₁⁺ in the brain per 1 Watt absorption did not change (< 4%) and Mean B₁⁺ in the brain for 1 Watt forward power changed (+3 to +13%)
- For the same forward power total absorption in the head models increased (5 to 21%) when the different Rx-only arrays were used.

Tissue specific analysis of SAR indicates:

- Copper width of 1.6 mm used to model wires of 32-loop helmet array caused only minimal increase in total absorption (5%) in comparison to the (14 to 21%) increase in absorption caused by thicker copper trace width (3 to 6 mm). Although, the difference in total absorption of array constructed of 3.2 or 6.4 mm wide copper was minimal (<5%) and geometry dependent (increased for staggered 16-loop array and decreased for 8-loop array.)
- Peak SAR (hot-spot) locations and intensities in some tissues changed when different receive-only inserts were used. Change in peak SAR distribution was pronounced (> 8%) for the 8 and 32 loop array geometry when compared to the staggered 16-loop design.

In conclusion, changes in local/global SAR and subtle changes in B₁⁺ field distributions were observed with the presence of Rx-only inserts from full wave simulation studies and experimentally obtained B₁⁺ maps. Thus, incorporation of the receive-only array effects are needed when evaluating SAR and designing RF transmit pulse waveform parameters for shimming and/or Tx-SENSE for 7 T MRI.

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REFERENCES

1. Liu F, Zhao H, Crozier S. On the Induced Electric Field Gradients in the Human Body for Magnetic Stimulation by Gradient Coils in MRI. *IEEE Trans Biomedical engineering*. 2003; 50(7)
2. Liu F, Zhao H, Crozier S. Calculation of electric fields induced by body and head motion in high-field. *J Magn Reson Imaging*. 2003; 161:99–107.
3. Angelone LM, Potthast A, Segonne F, Iwaki S, Belliveau JW, Bonmassar G. Metallic electrodes and leads in simultaneous EEG-MRI: specific absorption rate (SAR) simulation studies. *Bioelectromagnetics*. 2004; 25(4):285–95. [PubMed: 15114638]

4. Angelone LM, Vasios CE, Wiggins G, Purdon PL, Bonmassar G. On the effect of resistive EEG electrodes and leads during 7 T MRI: simulation and temperature measurement studies. *Magn Reson Imaging*. 2006; 24(6):801–12. [PubMed: 16824975]
5. Oh S, Ryu Y, Wang Z, Robb F, Collins CM. Influence of a Receive-array Coil on Specific Absorption Rate at 3T: Simulations and Experiments with Basic Geometries ISMRM. 2010
6. Ibrahim TS. Analytical approach to the MR signal. *MRM*. 2005; 54(3):677–82. [PubMed: 16088924]
7. Hoult DI. The principle of reciprocity in signal strength calculations: a mathematical guide. *Concepts Magn Reson*. 2000; 12:173–87.
8. Roemer PB, Edelstein WA, Hayes CE, Souza SP, Mueller OM. The NMR phased array. *Magnetic Resonance in Medicine*. 1990; 16(2):192–225. [PubMed: 2266841]
9. Keil B, Triantafyllou C, Hamm M, Wald LL. Design Optimization of a 32-Channel Head Coil at 7T ISMRM. 2010
10. Bottomley PA, Redington RW, Edelstein WA, Schenck JF. Estimating radiofrequency power deposition in body NMR imaging. *Magn Reson Med*. 1985; 2(4):336–49. [PubMed: 4094551]
11. Shellock FG. Radiofrequency energy-induced heating during MR procedures: a review. *J Magn Reson Imaging*. 2000; 12(1):30–6. [PubMed: 10931562]
12. Chen X, Hamamura Y, Steckner M. Numerical simulation of SAR for 3T whole body coil: effect of patient loading positions on local SAR hotspot. ISMRM. 2010 Stockholm Sweden.
13. Taflov, A.; Hagness, SC. *Computational Electrodynamics: The Finite-Difference Time-Domain Method*. Third Edition. Artech House; 2005.
14. Jean-Pierre B. Three-Dimensional Perfectly Matched Layer for the Absorption of Electromagnetic Waves. *Journal of Computational Physics*. 1996; 127(2):363–79.
15. Hand JW. Modelling the interaction of electromagnetic fields (10 MHz-10 GHz) with the human body: methods and applications. *Phys Med Biol*. 2008; 53(16):R243–86. [PubMed: 18653928]
16. Ibrahim TS, Abduljalil AM, Baertlein BA, Lee R, Robitail PM. Analysis of B1 field profiles and SAR values for multi-strut transverse electromagnetic RF coils in high field MRI applications. *Phys Med Biol*. 2001; 46(10):2545–55. [PubMed: 11686274]
17. Wright SM, Wald LL. Theory and application of array coils in MR spectroscopy. *NMR Biomed*. 1997; 10(8):394–410. [PubMed: 9542737]
18. Arun KS, Huang TS, Blostein SD. Least-squares fitting of two 3-d point sets. *IEEE Trans Pattern Anal Mach Intell*. 1987; 9(5):698–700. [PubMed: 21869429]
19. Hue Y-K, Ibrahim TS, Zhao T, Boada FE, Qian Y. A Complete Modeling System with Experimental Validation for Calculating the Transmit and Receive Fields, Total Power Deposition, Input Impedance, and Coupling between Coil Elements. ISMRM. 2008
20. Ibrahim TS, Hue YK, Tang L. Understanding and manipulating the RF fields at high field MRI. *NMR Biomed*. 2009; 22(9):927–36. [PubMed: 19621335]
21. Wolf S, Diehl D, Gebhardt M, Mallow J, Speck O. SAR simulations for high-field MRI: How much detail, effort, and accuracy is needed? *Magn Reson Med*. 2012
22. Seifert F, Wubbeler G, Junge S, Ittermann B, Rinneberg H. Patient safety concept for multichannel transmit coils. *J Magn Reson Imaging*. 2007; 26(5):1315–21. [PubMed: 17969165]
23. Van den Berg CA, van den Bergen B, Van de Kamer JB, Raaymakers BW, Kroeze H, Bartels LW, et al. Simultaneous B1 + homogenization and specific absorption rate hotspot suppression using a magnetic resonance phased array transmit coil. *Magn Reson Med*. 2007; 57(3):577–86. [PubMed: 17326185]

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Table 1

Effects of Rx-Only inserts on TEM Coil Scatter Parameters

	Scatter Parameters Head Model 1 (dB)					Scatter Parameters Head Model 2 (dB)				
	Head Only	Head Model + Rx Inserts				Head Only	Head Model + Rx Inserts			
		Cylindrical Array Copper Width (mm)				Helmet Array	Cylindrical Array Copper Width (mm)			
		8-Loop		16-Loop		32-Loop	8-Loop		16-Loop	
		3.2mm	6.4mm	3.2mm	6.4mm	1.6mm	3.2mm	6.4mm	3.2mm	6.4mm
S22	-6.99	-5.96	-6.13	-6.79	-6.69	-6.72	-6.57	-5.96	-6.11	-6.45
S44	-7.25	-6.18	-6.36	-6.74	-6.59	-7.00	-6.45	-5.83	-5.96	-6.41
S12	-15.88	-16.36	-16.22	-15.71	-15.66	-15.72	-16.74	-17.24	-17.09	-16.57
S13	-11.36	-11.89	-11.77	-11.37	-11.4	-11.70	-12.65	-12.63	-12.51	-12.18
Scatter Params	% change of magnitude in Head model 1					% change magnitude in Head model 2				
S22		12.59	10.42	2.34	3.54	3.14		7.23	5.43	<2
S44		13.11	10.84	6.09	7.95	2.88		7.39	5.72	<1
S12		-5.4	-3.8	<2	2.6	<2		-5.6	-3.9	2.0
S13		-5.9	-4.6	<-1	<-1	-3.8		<2	<2	5.6

TEM coil resonant frequency show minimal shifts (< 3MHz) when Rx inserts were used in simulations. Transmission values at 300 MHz from numerical simulations of coupling between adjacent ports (S12) and opposite ports (S13) for the two heads with different receive inserts are summarized. The coupling between ports of TEM coil minimally changes when different receive inserts were used (<6%). The Reflection of two ports of TEM coil and the changes with different Rx-inserts are also shown. The maximum change in reflection was <13%. The TEM coil model was not retuned for different Rx inserts but voltage of each port was scaled for equal transmission.

Table 2

Effects of Rx-Only inserts on B_1^+ distribution of TEM Coil

B_1^+ in Brain (WM+GM+CSF+ Midbrain+ Cerebellum) Model Weight for Head Models 1 / 2: 3.6 Kg/4.7 Kg	B_1^+ per 1 Watt Absorbed Power Mean (μ T), CV= σ/μ		B_1^+ per 1 Watt Forward Power Mean (μ T)		Percent Change in B_1^+ for 1 Watt Absorbed Power Mean, CV= σ/μ .		Percent Change in B_1^+ for 1 Watt Forward Power Mean	
	Head 1		Head 2		Head 1		Head 1	
							Head 1	Head 2
Cylindrical	Head only	0.76	0.29	0.60	0.27	0.68	0.53	
	Head+8-loop array copper width 3.2 mm	0.76	0.30	0.59	0.27	0.74	0.58	9
	Head+8-loop array copper width 6.4 mm	0.76	0.30	0.59	0.27	0.73	0.57	8
	Head+16-loop array copper width 3.2 mm	0.79	0.29	0.61	0.27	0.75	0.58	9
	Head+16-loop array copper width 6.4 mm	0.79	0.29	0.61	0.27	0.77	0.58	9
Helmet	Head+32-loop array copper width 1.6 mm	0.77	0.28			0.70		3

B_1^+ in brain were calculated for 1 Watt absorbed power and 1 Watt real forward power. The B_1^+ distribution for 1 Watt absorption in the brain did not change appreciably when different receive inserts were used (< 4%). Subtle changes in B_1^+ distribution (< 14%) were observed with different receive inserts for the same real forward power.

Table 3

Effects of Rx-Only inserts on global SAR in head models

RF Absorption: Global SAR Model Weight for Head Models 1 / 2: 3.6 Kg/4.7 Kg		Total Absorbed Power (W) for Peak Local SAR =10 W/Kg Per 10gm		Total Absorbed Power (W) for 1Watt Forward Power		Percent Change in Total Absorbed Power (W) for Peak Local SAR =10 W/Kg Per 10gm		Percent Change in Total Absorbed Power for 1Watt Forward Power	
Cylindrical	Head only	Head 1	Head 2	Head 1	Head 2	Head 1	Head 2	Head 1	Head 2
	Head+8-loop array copper width 3.2 mm	11.35	13.76	0.94	0.95	11.83	10.12	21	19
	Head+8-loop array copper width 6.4 mm	11.20	13.58	0.92	0.93	10.41	8.74	18	16
	Head+16-loop array copper width 3.2 mm	11.68	14.37	0.92	0.91	15.15	15.07	18	14
	Head+16-loop array copper width 6.4 mm	12.01	14.37	0.94	0.91	18.42	15.07	21	14
Helmet	Head+32-loop array copper width 1.6 mm	9.07		0.82		-10.62		5	

Total absorption in head models were calculated for allowable peak local SAR of 10 W/Kg per 10 gm and 1 Watt real forward power. Changes in absorption for the same real forward power indicate a change in radiation of the TEM coil when the different RX-only arrays were used. Total absorption per Watt forward power increased (14 to 21 %) for the 8 and 16 loop cylindrical arrays. Copper width of 1.6 mm used for modeling the 32-loop helmet array did not increase RF absorption substantially (5%).

Table 4

Effects of Rx-Only inserts on local SAR in head models

RF Absorption: Local SAR Model Weight for Head Models 1 / 2: 3.6 Kg/4.7 Kg		Peak Local SAR for Mean $B_1^+ = 2 \mu T$ in Brain (WM+GM+CSF+ Midbrain+Cerebellum) W/Kg Per 10 gm		Peak Local SAR for 1 Watt Forward Power W/kg Per 10 gm		Percent Change in Peak SAR for Mean $B_1^+ = 2 \mu T$ in Brain(WM+GM+CSF+ Midbrain+Cerebellum)		Percent Change in Peak SAR for 1 Watt Forward Power	
Head only	Cylindrical	Head 1	Head 2	Head 1	Head 2	Head 1	Head 2	Head 1	Head 2
		6.72	8.99	0.77	0.64				
		7.20	9.68	0.98	0.81	7.14	7.68	27	27
		7.17	9.65	0.95	0.79	6.70	7.34	23	23
		6.83	8.95	0.97	0.76	<2	<-1.0	26	19
Helmet	Head+32-loop array copper width 1.6 mm	6.85	8.95	1.01	0.76	<2	<-1.0	31	19
		7.71		0.96		14.69		25	

SAR were obtained for mean B_1^+ in brain of $2 \mu T$ and 1 Watt real forward power. Peak local SAR intensity in the head models changed when the different RX-only array were used. Peak local SAR changed -1 to $+15\%$ for the same B_1^+ in brain and $+19$ to $+31\%$ for the same real forward power.