Simulation-Based Phased-Array Optimization Using an Efficient Method for Realistic Coil Modeling

M. Korn[1], S. Lambert[1], X. Maître[1], and L. Darrasse[1]
[1]IR4M (UMR8081), Université Paris-Sud XI - CNRS, Orsay, France

Introduction

To correctly simulate the electromagnetic (EM) field distribution of a receive-only phased-array coil, properties like matching, element and preamplifier decoupling have to be included. Especially the implementation of the circuitry connected to the coil can be challenging. Some previously described approaches either neglect the properties of the circuitry and calculate the field created by a homogeneous current in the coil [1], while others suggest an (iterative) co-simulation of electromagnetic fields and the circuitry [2], which requires the joint use of different software. In this work, we describe a method that uses a full wave EM simulation to calculate the EM fields, while the effect of the circuitry is substituted by a discrete impedance R_{port}. The value of R_{port} is directly derived from the reflection coefficient of the preamplifier input and the coil impedance. The presented approach also includes sample losses, distributed capacitors, and geometrical and capacitive element decoupling. The method is demonstrated on a 6-channel receive-only coil for the ^{3}He resonance frequency at 1.5 T (48.7 MHz). Three different geometries are compared in order to find the configuration that yields maximum sensitivity and minimal g-factors for parallel imaging [3].

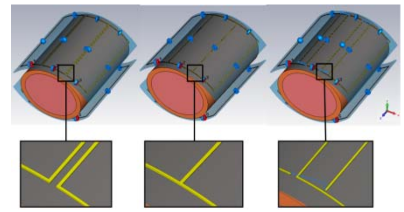

Fig. 1: Model of the loaded phased-array coils with the 3 decoupling methods: Gap (left), shared conductor (center) and overlap design (right).

Materials and Methods

Geometrical model: The simulated coils consisted of two PMMA carriers (anterior and posterior parts), each of which carried 3 rectangular coil elements (Fig. 1). Each element was segmented by four discrete capacitors. As a load, an elliptical cylinder with the electrical properties of the human thorax was inserted between the PMMA carriers. Three ways of element alignment were compared: 1. adjacent elements were separated by a gap, 2. adjacent elements shared the same conductor and mutual inductance was compensated by the values of the capacitors, 3. adjacent elements were critically overlapped to minimize mutual inductance.

Circuit model: In practice, each element of a phased-array coil is connected to a preamplifier with high input reflection coefficient Γ_{IN} (Fig. 2). A transformation network between the coil and the preamplifier transforms the complex preamplifier input impedance to the high real impedance R_{port} seen by the coil [4, 5]. Assuming, that $\Gamma_{IN}=\Gamma_C$, and knowing R_{coil} and Γ_{IN}, one can calculate $R_{PORT}=R_{COIL}(\Gamma_{IN}-1)/(1-\Gamma_{IN})$.

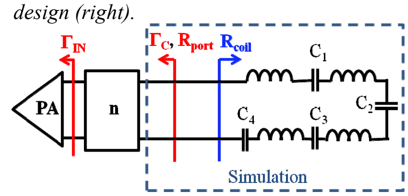

Fig. 2: Receive coil, consisting of tuned coil, matching network, impedance transformation (n) and preamplifier (PA). Only the part in the dashed box is considered in the EM field simulations, while the connected circuitry is substituted by R_{port}.

Simulation workflow: The model was implemented in CST Microwave-Studio (CST AG, Darmstadt, Germany) and simulations using the time-domain transient-solver were performed. The workflow follows the process along which phased array coils are usually fabricated. The following steps were subsequently carried out:

- Tuning and Matching: A first simulation was performed, in which only one element was considered, in order to find the optimal values of $C_{1\text{-}4}$ and R_{port} for matching at 48.7 MHz. Due to the symmetry of the phased-array coil, this had to be done twice: once for a central element and once for a lateral element. Matching was considered achieved when S_{11} was lower than -15 dB.
- The value of the total tuning capacitance for an element was compared to the value obtained in an RF-workbench measurement, where a real coil element of a shared conductor array, formed of adhesive copper tape on a PMMA carrier, was tuned to 48.7 MHz.
- Decoupling: For the shared conductor and the overlap designs, further simulations were performed, in which two matched, adjacent elements were considered in order to find the optimal shared capacitor values and the optimal overlap, respectively.
- Preamplifier decoupling: R_{port} was then changed from the matched condition to a value that represented an input reflection factor of Γ_C=0.95. Then the final simulation was performed, during which the spatial sensitivity (H/√P) of the complete array was calculated.

Config.	Slice	$\langle S_0 \rangle$	med(g_2)	med(g_3)
Gap	Ax	1.0	1.07	1.43
Shared	Ax	0.96	1.07	1.45
Overlap	Ax	0.97	1.09	1.57
Gap	Cor	1.0	1.05	1.39
Shared	Cor	0.99	1.06	1.43
Overlap	Cor	0.99	1.07	1.51

Tab. 1: Mean sensitivities $<S_0>$ and median g-factors for 2- and 3- fold undersampling in left-right direction in an axial (Ax) and a coronal (Cor) slice at the center of the sample.

Postprocessing: The 3D complex H/√P-maps were exported and the receive-sensitivity $S=H_1^{(-)}/\sqrt{P}$ was calculated for each coil element [6]. The single coil sensitivities were finally combined to obtain the array-sensitivity S_0. g-Factor maps were calculated for coronal and axial slices while assuming the signal originates from a region of the size of the human lung.

Results and Discussion

Tuning and matching: For the total capacitance of the series circuit formed by $C_{1\text{-}4}$, the simulations yield values between 10.7 pF and 12.4 pF for the central element, and between 11.6 pF and 13.0 pF for the lateral element. Within the component tolerances and the measurement accuracy, the calculated values were equal to the values obtained in the RF-workbench measurement (12 pF). *Decoupling:* When a second matched element was added, mutual coupling led to a frequency split of Δf=8 MHz in the gap configuration. In the overlap and shared conductor configurations, this coupling could be reduced such that no frequency split could be observed and S_{21} was well below -15 dB. *S_0 and parallel imaging:* Fig. 3 shows 1/g-maps for an axial slice. In all configurations, the lowest g-factors were achieved in the center. Tab. 1 shows the average S_0-values for an axial and a coronal slice in the center of the sample, and the median values of the g-factors for 2- and 3-fold undersampling in the left-right direction. The differences in sensitivity were below 5% for the different geometries, which can be attributed to rather small changes of the coil surface area with respect to the total coil size. The gap configuration showed the highest S_o and lowest g-factors. Since the H_x- and H_y-components contribute to the coil sensitivity, even the sensitivity maps of the gap configuration did not show severe signal cancellations between adjacent elements.

Conclusion

An efficient method for modeling and simulating phased-array coils was presented. It takes relevant coil properties, like element decoupling and preamplifier decoupling into account. Three configurations - gap, shared conductor, and overlap - were compared for a 6-element phased-array coil. The baseline sensitivity only differs within 5%, whereas the g-factor performance shows the superiority of the gap design and the shared conductor configuration.

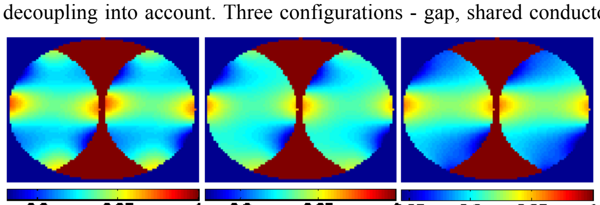

Fig. 3: 1/g maps for an axial slice in the center of the simulated array for 2-fold undersampling in left-right direction. Gap (left), shared conductor (center),overlap (right) design.

Acknowledgements

The authors would like to thank Titus Lanz, Rapid Biomedical, Rimpar, Germany, for providing useful information.

References

[1] G Giovannetti et al. Conc Mag Res B 31B:140–146 (2007) [2] M. Kozlov, R. Turner, JMR 200: 147–152 (2009). [3] K. P. Pruessmann et al. MRM 42:952–962 (1999). [4] P. B. Roemer et al. MRM 16:192-225 (1990) [5] A. Reykowski et al. MRM 33:848-852 (1995). [6] D. I. Hoult Conc. Mag. Res.12(4):173-187 (2000).