Radiofrequency Coil Array Design and Optimisation for Magnetic Resonance Low Field Imaging

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Abstract. *Radiofrequency (RF) coil phased arrays are getting more and more important for accelerating the imaging speed and for gaining better signal to noise ratio (SNR) in magnetic resonance imaging (MRI). The approach is conceptually similar to phased array used in radar techniques hence it is used to be called MRI phased array coils. To get maximum benefits from this technique, coil and preamp decoupling and coil geometry optimization are necessary to ensure independence of the individual coil channels. Qualitative design and a method for optimization of geometric properties of the coil elements in phased arrays, with aim to increase SNR, G-factor and to limit noise correlation, are proposed in this paper. Simulating by the finite element method (FEM) using Comsol Multiphysics we obtained the sensitivity maps of coils. The introduced Matlab program is primarily calculating the G-factor along with other parameters that can be calculated from sensitivity maps. By an optimization algorithm the program is setting the parameters of the coil and afterwards is driving the FEM simulations.*

Keywords: MRI, coil array optimization, phased array

1. Introduction

Parallel Imaging

Usually, the data are acquired sequentially using different magnetic field gradients. Parallel imaging technique in MRI uses spatial information about the origin of detected MR signal from sensitivity maps of particular RF receivers of the array. This information may be used for the image generation. As coil sensitivity map does not depend on the examined object it can be obtained prior the measurement and just once for each coil. Thus, it can significantly shorten the time of image acquisition, e.g. by using less phase encoding steps (without losing the image quality), or increase the image quality in the normal acquisition time. Careful design of suitable phased coil array is essential for optimal parallel imaging [1], [2].

Receivers in array are connected to the independent preamplifier, amplifier and separately digitalized. Data from each channel are later combined in optimal way with focus on the origin of the signal by Sensitivity Encoding (SENSE) reconstruction algorithm or Generalized Auto-calibrating Partially Parallel Acquisitions (GRAPPA) [3], [4], etc.. Using these methods, it is possible to acquire SNR of local coil with a field-of-view (FOV) typical to a volume receiver [5].

Noise in Paralel Imaging - Geometry Factor

Serious limitation of all techniques in MR is level of noise or SNR. Phased array techniques and parallel imaging is not an exception. As was already mentioned, in arrays is higher number of individual coils used instead of one global. Because one part of noise is generated by the sample which is hard to eliminate, it is possible to increase the SNR by using the array coils. Applicability of array for parallel imaging might be represented by the so called geometry factor (G-factor), that is most depended on geometry of the coil and can be defined by the formulas of Pruessmann [2]:

$$g = \frac{SNR^{full}}{SNR^{red}\sqrt{R}} \quad , \tag{1}$$

where *g is a* geometry factor and it is always equal or higher than one, SNR^{full} is SNR in full encoding acquisition, SNR^{red} denotes SNR in sample-reduced acquisition and R is a factor by which the number of samples is reduced in comparison to full acquisition. For SENSE reconstruction was derived a formula:

$$g_\rho = \sqrt{\left[\left(S^H \Psi^{-1} S\right)^{-1}\right]_{\rho,\rho} \left(S^H \Psi^{-1} S\right)_{\rho,\rho}} \tag{2}$$

where g_ρ is a local geometry factor, ρ denote the index of the voxel, S^H transposed sensitivity matrix, ψ receiver noise matrix. For the GRAPPA reconstructions a different formula for quantitative G-factor must be used [4].

Decoupling

Mutual inductances and parasitic capacitances may cause coupling - an undesired transfer of signal and also of the noise between the coils. This causes loosing of the spatial information and also decreases the SNR. So, the reduction of this unwanted interactions between coils with overlapping FOVs is critical in phased array techniques. This might be performed in several ways (or their combination): By the mutual position of the coils in array (the overlap of the neighboring coils or as in our case a gap - distance between the coils); By "preamplifier decoupling" using either high impedance or low impedance input preamplifier; By coil decoupling by lumped elements mutual capacitors or inductances; By coil shielding (passive or active), etc. More information can be found in [6], [1].

2. Subject and Methods

Analytical precalculations

For the study of the butterfly coil behavior have been used an analytical calculations in Wolfram Mathematica derived from Biot-Savart law:

$$H(r) = \frac{I}{4\pi}\int_l \frac{dl \times r}{\left|r^2\right|} \tag{3}$$

Vector of magnetic filed ***H(r)*** is calculated in simplified model as four infinite strip conductors fed by current *I.* Thickness of the strips is here neglected. For one strip were derived formulas (4) and (5). The x–component of magnetic field H_x can be written as follows:

$$H_x = \frac{15}{2\pi}\left[\tan^{-1}\left(\frac{-a-x+f}{y+b}\right) - \tan^{-1}\left(\frac{a-x+f}{y+b}\right)\right] \tag{4}$$

For the y–component of the magnetic field H_y was written the following expression [7]:

$$H_x = \frac{15}{4\pi}\left[Log\left\{(-a-x+f)^2 + (y+b)^2\right\} - Log\left\{(a-x+f)^2 + (y+b)^2\right\}\right] \tag{5}$$

where *a* is the width of the strip, *x* and *y* are coordinates in two dimensional Cartesian coordinate system, *f* is a shift of the strip on *x* axis, *b* is a shift of the strip on *y* axis.

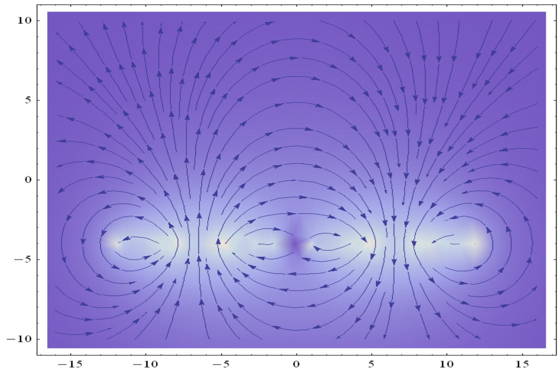

Fig. 1. Magnetic field $H_{x,y}(x,y)$ of the one butterfly coil from Fig.2, calculated from equations (4), (5).

Design of coils

Small cavity of the G-Scan together with B_0 direction perpendicular to scanner cavity, does not allow usage of typical design of phased array coil. Hence a design combined from two square loops and two so called butterfly coils was selected. The advantage of butterfly coil is a significant sensitivity to the longitudinal magnetic field components (this means field perpendicular to the face of the coil).

FEM Analyses – Comsol multiphysics

For FEM analyses Comsol Mutliphysics package with an interface to Matlab was used. This allows preparing of all models by a code written in Matlab and also running all Comsol simulations from Matlab. Data extracted from the simulations are processed and parameters like G-factor might be calculated. According to the calculated parameter new dimensions of the coil are proposed and calculated by Comsol Kernel. Due to the long duration (minutes) of each simulation and many parameters of the coil that are adjusted, a short optimization algorithm should be used. As the coil parameters can slightly change with the loading, the model will always slightly differ. So, the optimization convergence limit can be set on quite high level. Finally the optimal setting of the array in seven steps of the optimization algorithm was reached.

3. Results

A method for optimization of phased array receivers uses simulations of electromagnetic fields by finite element methods available in Comsol Multiphysics. Optimization routine was written in Matlab. Description of the coil array and setting of the parameters of the Comsol simulation was based on common interface of the Matlab and Comsol. An optimal array setting for SENSE G-factor was reached by adjusting of the seven dimensional parameters, in seven steps of the optimization algorithm.

Table 1. Results of the optimization steps of the 4-channel phased array for 3He lung imaging in ESAOTE G-Scan. Optimized on G-factor calculated by (2) with R=4

Step	**0**	**1th**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**
Width of square loop	19	24	24	24	24	24	24	24
Length of Square loop	24	20	26	20	20	20	23	26,5
Widht of copper strip sq. Loop	1,5	1	0,5	0,5	0,5	0,5	0,5	0,5
Width of butterfly coil	8	5,5	5,5	6,5	5,5	5,5	5,5	5,5
Length of butterfly	30	25,5	33	38	32,5	40	40	40
Width of butterfly coil strip	1,5	1	1,5	1	1	0,5	0,5	0,5
Gap on butterfly	5	4,5	3	4	3	4	3	3
G-Factor	**3,02**	**2,19**	**2,04**	**1,96**	**1,84**	**1,73**	**1,67**	**1,67**

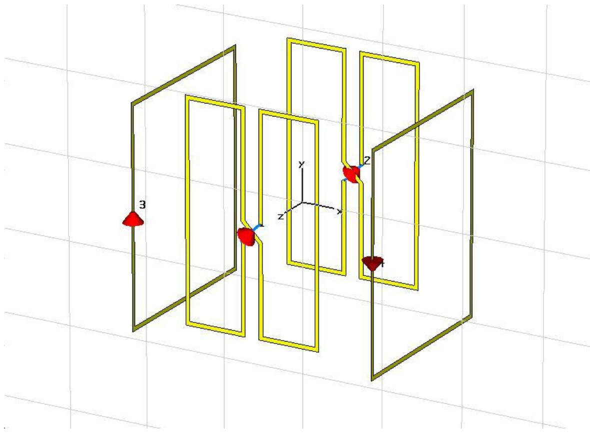

Fig. 2. Model of the 4 channel phased array coil system designed for ESAOTE G-Scan tomograph

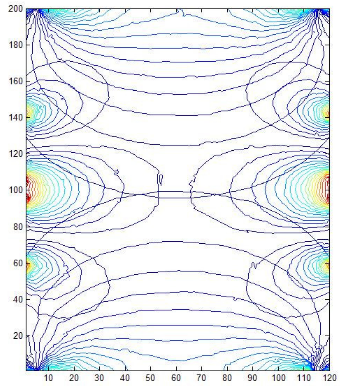

Fig. 3. Coil sensitivity maps of the array from Fig.2 calculated in Comsol Multiphysics

4. Discussion and Conclusion

The paper is proposing a method for optimization of phased array resonators by using simulations of electromagnetic fields by finite element methods in Comsol Multiphysics and optimization routine written in Matlab. Description of the coil array and setting of the parameters of the simulation is based on common interface of the Matlab and Comsol. By using of this method the four channel coil array for ESAOTE G-scan for thorax imaging was designed and optimized for SENSE G-factor. Currently the coil was manufactured and currently is under testing. Advantage of the proposed method is in versatility of the usage, in effective and fast calculation and in relative simplicity.

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References

[1] Ohliger, M.A. and D.K. Sodickson, An introduction to coil array design for parallel MRI. *Nmr in Biomedicine*, 19(3): p. 300-315, 2006.

[2] Pruessmann, K.P., M. Weiger, M.B. Scheidegger, et al., SENSE: Sensitivity encoding for fast MRI. *Magnetic Resonance in Medicine*, 42(5): p. 952-962, 1999.

[3] Griswold, M.A., P.M. Jakob, R.M. Heidemann, et al., Generalized Autocalibrating Partially Parallel Acquisitions (GRAPPA). *Magnetic Resonance in Medicine*, 47(6): p. 1202-1210, 2002.

[4] Breuer, F.A., S.A.R. Kannengiesser, M. Blaimer, et al., General Formulation for Quantitative G-factor Calculation in GRAPPA Reconstructions. *Magnetic Resonance in Medicine*, 62(3): p. 739-746, 2009.

[5] Roemer, P.B., W.A. Edelstein, C.E. Hayes, et al., The Nmr Phased-Array. *Magnetic Resonance in Medicine*, 16(2): p. 192-225, 1990.

[6] Lee, R.F., R.O. Giaquinto, and C.J. Hardy, Coupling and decoupling theory and its application to the MRI phased array. *Magnetic Resonance in Medicine*, 48(1): p. 203-213, 2002.

[7] Frollo, I., P. Andris, J. Přibil, et al., Magnetic Field Measurement of a Planar Coil Using Magnetic Rezonance Imaging Method. *Measurement Science Review*, 10(3): p. 97-101 2009.