SENSE Optimized RF Coil Design with Target Field Method

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Purpose

The B1 field distribution of the individual coils in a SENSE imaging array determines the SNR within a target volume of interest (VOI). Weiger et al attempted to find optimized SENSE coils by simulating various pre-defined coil topographies (*MRM 45: 495-504, 2001*). This method is restricted by the limited number of coils simulated, and the result will most likely be not the most optimum. Our goal is to solve the inverse problem of calculating the coil topography, given the target volume and reduction factor. The SNR in a SENSE-MR image SNR_{sense} is inversely proportional to the *g-factor*. One can formulate the *g-factor* in terms of the B1 distribution (sensitivity profiles) of the coils. Then, by specifying the geometry of the desired coil former and using Finite Element Mesh (FEM), it is possible to find the surface current distribution to maximize SNR_{sense}, by minimizing ($1/SNR_{sense}$) in the VOI using a *least squares procedure*.

Methods

Pissanetzky has proposed a method to design gradient coils where a target field is specified and the surface current distribution is calculated to achieve the desired target field (*Meas.Sci. Technol. 3:667-673, 1992*). In his approach, the surface current distribution on a predefined surface (coil former) is calculated by using a *least squares procedure* to minimize the difference between the user-defined target field and the field generated by the calculated current distribution.

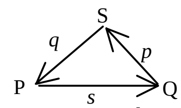

Fig.1. Triangular element of the FEM

The coil system consists of wires placed on a predefined surface in 3D space, which can be approximated by a surface current density J_s. The surface can be any prescribed shape but a cylindrical surface was chosen for the presented study. The surface on which J_s flows can be approximated by a FEM consisting of flat triangular elements (Fig.1). For the derivation of the forward problem, we will follow the convention presented in Pissanetzky's article. In this element, J_s must satisfy the continuity equation, whose solution gives $J_{su}= \partial\sigma/\partial v$, $J_{sv}= -\partial\sigma/\partial u$, where (u,v,w) is the system of coordinates in the plane of the triangle and σ is called the *stream function*. Solution of these equations gives J_s,(Eq 1). Here, S^e is the area of the triangle and σ_p, σ_q and σ_s are the values of σ at nodes P, Q, S, respectively. Using Eq.1, one can calculate the magnetic vector potential $\boldsymbol{A}$ and magnetic flux density $\boldsymbol{B}$ generated by J_s at any point in space (Eq. 2. Note that only u-component is given here). Details were given in Pissanetzky's article and will be omitted here. Using Eq.2 and the transformation between the (u,v,w) and the (x,y,z) coordinate systems, the field components B_x, B_y and B_z generated by the current density in each element can be calculated. Then, the total $\boldsymbol{B}$ field is determined by summing over all the elements of the mesh.

$$J_s = \frac{1}{2S^e}(\sigma_p \cdot p + \sigma_q \cdot q + \sigma_s \cdot s) \quad (1)$$

$$B_u^e = \frac{-\mu 0}{4\pi} \cdot J_{sv} \cdot \frac{\partial}{\partial w} \int_{S^e} \frac{dS'}{r} \quad (2)$$

The SNR_{sense} and the *g-factor* in the ρth pixel are given by Eq.3-4, respectively (Pruessmann et al, MRM 42:952-62, 1999). Here, S is the coil sensitivity matrix R is the reduction factor, and Ψ is the receiver noise matrix (Eq.5), where $B_\gamma(\mathbf{r}_i)$ is the field generated by the γth coil at point $\mathbf{r}_i$. Once SNR_{sense} is formulated in terms of coil $\boldsymbol{B}$ fields, it is possible to calculate the current density distribution that maximizes the SNR_{sense} within a VOI. The current distribution on a cylinder with 13cm diameter was calculated using the proposed method. The VOI was a 5cm long cylinder with 7cm diameter. The coils, which were the resulting current paths, were etched on a flexible copper clad board and wrapped around an acrylic cylinder. The array was made up of two coils placed across each other in the horizontal direction. The coil array was tuned to 64MHz to operate inside a 1.5T Philips Eclipse system. Isolation between the coils was achieved by a lumped element network. The final coils had S11 around –28dB and an isolation factor better than –25dB.

$$\mathrm{SNR}_{\mathrm{sense},\rho} = \mathrm{SNR}_{\mathrm{full},\rho} / (g_\rho \cdot \sqrt{R}) \quad (3)$$

$$g_\rho = \sqrt{\left((S^H \cdot \Psi^{-1} \cdot S)^{-1}\right)_{\rho,\rho} (S^H \cdot \Psi^{-1} \cdot S)_{\rho,\rho}} \quad (4)$$

$$\Psi_{\gamma,\gamma'} = \sum_{i=1}^{N} B_\gamma(\mathbf{r}_i) \cdot B_{\gamma'}(\mathbf{r}_i) \quad (5)$$

Results

The sensitivity profile of this new coil was measured using a CuSO4 filled cylindrical phantom with 7cm diameter (Fig.2.a). Expected B field of this new coil structure is calculated by Biot-Savart Law for comparison and illustrated in Fig.2.b. The sensitivity profile of a standard rectangular coil is also calculated and shown in Fig.2.c. A reduced FOV imaging experiment was also run with R=2 and the resulting aliased image and SENSE reconstructed image were shown in Fig.3.

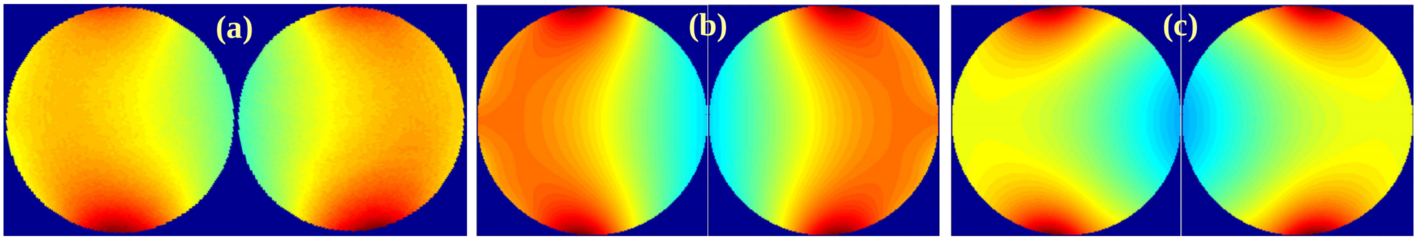

Fig.2. Sensitivity profiles of the SENSE optimized coil: (a) Measured; (b) simulated. (c) Sensitivity profile of standard rectangular coil. Profiles of the left and right coils are shown side by side.

Discussion

It can be seen from Fig.2.a-b that the measured sensitivity profiles of the designed coil are in accord with the calculated maps. Improved uniformity of the individual coils can be seen when the new design in Fig.2.b is compared with the standard design of Fig.2.c. The average SNR_{sense} for the new coil and the standard design within the VOI were calculated to be 544 and 470, respectively. The proposed design was tested with a simple 2-coil, cylindrical structure. However, using the same idea, more complicated designs with increased number of coils and reduction factors can easily be designed. Moreover, the geometry of the coil can be any arbitrary shape, e.g. one that wraps tightly around a body part.

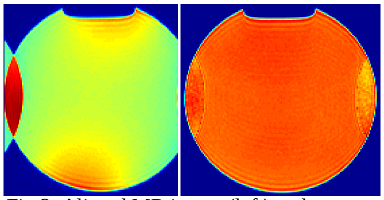
Fig.3. Aliased MR image (left) and SENSE reconstructed image (right).