Target Field Based RF Phase Gradient Transmit Array for 3D TRASE MRI

Jesse Bellec[1], Scott B. King[1,2], Chen-Yi Liu[1], and Christopher P. Bidinosti[3]
[1]*Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba, Canada,* [2]*National Research Council of Canada, Winnipeg, Manitoba, Canada,* [3]*Physics, University of Winnipeg, Winnipeg, Manitoba, Canada*

INTRODUCTION: Transmit array spatial encoding (TRASE) [1] is a novel gradient-free imaging technique relying on Tx RF phase gradients expressed as $\mathbf{B_1} = |\mathbf{B_1}|\exp(i\varphi_1(\mathbf{r}))$, to spatially encode the transverse magnetization as $M_T = |M_0|\exp(i\varphi_1(\mathbf{r}))$, where $\varphi_1(\mathbf{r}) = 2\pi\mathbf{k}_1\cdot\mathbf{r}$. Ideal phase gradients have a uniform $|B_1|$ and strong-linear $\varphi_1(\mathbf{r})$ over a large volume. To traverse *k*-space along one dimension in TRASE, 2 distinct phase gradients along that dimension are required [1], totaling to 6 phase gradients to achieve 3D *k*-space traversal. Using a target field based approach first used to design a *z*-phase gradient [2], an initial array of Tx phase gradients coils have been obtained that display the potential to perform 3D TRASE MRI at 3T.

APPROACH: Previous work had demonstrated that the target field method [3] could be adopted to develop coils on a cylinder that generate transverse fields by specifying the target field in cylindrical components B_ρ or B_φ [2]. For a solenoidial MRI system, the B_0 field is directed along the *z*-axis, so the transverse components are in the *xy*-plane. The ideal RF phase gradient field is thus modeled as $\mathbf{B}_{1,\mathbf{r}}=B\cos(\mathbf{g}_1\cdot\mathbf{r}+\theta)\mathbf{x}\pm B\sin(\mathbf{g}_1\cdot\mathbf{r}+\theta)\mathbf{y}$, where $\mathbf{g}_1$ is the phase gradient, $\mathbf{r}$ is the direction of the gradient, and θ is an arbitrary phase shift. The field is then transformed into cylindrical coordinates and apodized [2,3]. The procedure to obtain an actual winding pattern is outlined in [2].

Analyzing each surface current Fourier component $F_m(k)$ gave insight into the "building blocks" of the transverse phase gradient fields $\pm g_{1,x}$ and $\pm g_{1,y}$, revealing that a set of 3 weakly coupled coils could be used to generate the 4 phase gradients. This was accomplished by analyzing the currents near z=0, allowing them to extend to $z = \pm\infty$, and then substituting them into Eq.4 of [4]. The fields generated by the first 3 terms (m = 0, 1, and 2) were calculated and this knowledge directly led to the design of coils that best generate these fields.

RESULTS/DISCUSSION: The surface current Fourier components $F_m(k)$ for a $g_{1,y}$ phase gradient target field were calculated and contained all m's for $m\geq0$, where the dominant terms were m=0, 1, and 2. For the terms m=1 and m=2, the surface current at z=0 is $\mathbf{F}_m=C_m\sin(m\varphi)\mathbf{z}$, where C_m is a weighting factor. The $\mathbf{F}_1=C_1\sin(\varphi)\mathbf{z}$ current generates a uniform B_x field $\mathbf{B}_1=\beta_1\mathbf{x}$, and the $\mathbf{F}_2=C_2\sin(2\varphi)\mathbf{z}$ current generates a field of the form $\mathbf{B}_2=\beta_2(x\mathbf{x}-y\mathbf{y})$, where β_1 and β_2 are constants. The m=0 current resembles a first order gradient coil [3], where the field near the center of the coil can be expressed as $\mathbf{B}_0=-(2\beta_0)z\mathbf{z} + \beta_0(x\mathbf{x} + y\mathbf{y})$, where β_0 is a constant. If $\beta_0=\beta_2=\beta$, then adding the fields yields the following field $\mathbf{B}_{\sin}=2\beta(y\mathbf{y}-z\mathbf{z})$. Ignoring the *z*-component which is parallel with B_0, this is a linear B_y field. To first approximation, it is the sine component of the target field. Similarly, to first approximation $\mathbf{B}_1$ is the cosine component ($\mathbf{B}_{\cos}=\mathbf{B}_1=\beta_1\mathbf{x}$). It is believed that the components for m>2 are attempting to generate the higher order terms in the cosine and sine fields, but introduce unwanted concomitant effects that are necessary to satisfy Maxwell's equations.

Constructing the m=1 and m=2 coils is a relatively easy task, they can each be built from a birdcage resonator that has the appropriate mode tuned to the frequency of interest, 123.2 MHz. These coils are shown in Fig. 1(a) and Fig. 1(b). The m=0 target field coil needs to be relatively long to create a linear field over a reasonable length [3], so special emphasis was placed on designing a better coil. Using a method outlined by D. Hoult [5], a 4 ring coil (on a sphere) with the appropriate current magnitudes and directions could generate the $\mathbf{B}_0$ field over a much larger region. This coil is shown in Fig. 1(c), where the current ratio of outer/inner rings is 1.12 and the rings in $+z$ run opposite to the rings in $-z$.

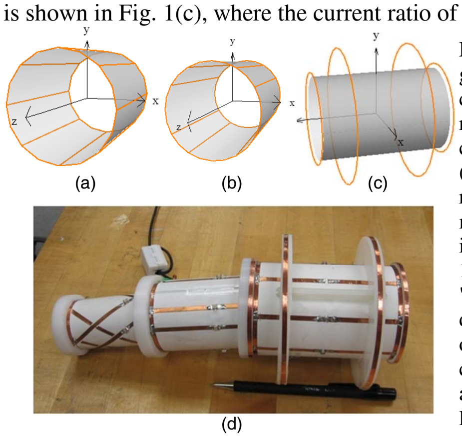

Fig 1: RF Tx phase gradient coil array. (a) 6.4 cm diameter 8 leg birdcage resonant on 1st mode, (b) 5.4 cm diameter 12 leg birdcage (with zero current legs removed) resonant on 2nd mode, (c) 4 ring coil with inner/outer ring current ratio 1.12 and operated in "Maxwell" mode. Inner ring diameter of 10.95 cm and outer ring diameter of 6.9 cm. (d) Constructed Tx array elements. All coil lengths are 10 cm.

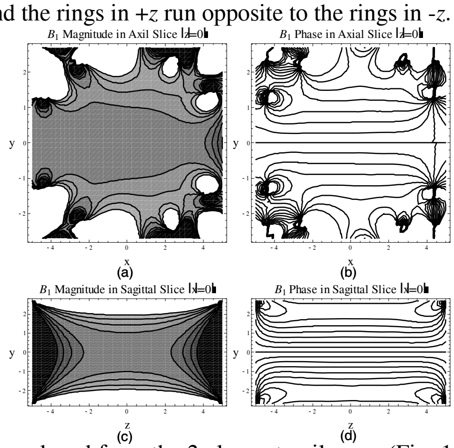

Fig 2: Simulated field plots of the transverse phase gradient coil array of Fig. 1, producing a $g_{1,y}$ phase gradient. (a) Normalized transverse magnitude $|\mathbf{B_1}|$ in central axial plane, (b) phase plot in central axial plane, (c) normalized $|\mathbf{B_1}|$ in central sagittal plane, (d) phase plot in central sagittal plane. The simulated region is $(x,y,z) = (\pm2.7, \pm2.7, \pm10)$ cm. The magnitude plots are 5% intervals with respect to the central value.

Using the proper weighting (current magnitudes), the magnetic field produced from the 3 element coil array (Fig. 1(a,b,c)) was simulated using a Biot-Savart calculation. The results are presented in Fig. 2, where Fig. 2(b,d) demonstrate that the phase is linear over a large region. The normalized magnitude plots in Fig. 2(a,c) demonstrate that the transverse fields are uniform to within 5%, but over a limited region. It is important to note that the 8 leg birdcage in Fig. 1(a) can have 2 orthogonal drive legs (separated by 90°), so it can be used to create a uniform field in either B_x or B_y. Therefore, by selecting the appropriate drive leg, as well as magnitude and polarity on each coil, all 4 phase gradient fields ($\pm g_{1,x}$ and $\pm g_{1,y}$) can be generated. Initial construction of the array elements, shown in Fig. 1(d), display similar phase gradient performance to simulated predictions.

CONCLUSIONS: Based on a target field method, we have designed a minimal set of Tx array elements with minimal coupling that can be driven to produce a set of six RF phase gradients necessary for 3D TRASE MRI at 3T.

REFERENCES: [1] JC Sharp and SB King, Magn Reson Med. 63:151-161(2010), [2] J Bellec *et al*., Proc. ISMRM #723 (2011), [3] R Turner, J. Phys. D: Appl. Phys. **19**, (1986) L147-L151. [4] CP Bidinosti *et al*., J Magn Reson **177**, 31 (2005), [5] DI Hoult and R Deslauriers, Magn Reson Med. 16: 411-417 (1990).