3D Imaging in a Portable MRI Scanner using Rotating Spatial Encoding Magnetic Fields and Transmit Array Spatial Encoding (TRASE)

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PURPOSE: MRI could find wider applicability if low-cost, portable systems were available for siting in unconventional locations such as ICUs, physician offices, ambulances, or rural healthcare sites. The development of a previously described portable (<100kg) MRI scanner for brain imaging[1] is advanced with the implementation of 3rd axis encoding using the TRASE technique[2,3].

METHODS: Our 2D axial plane imaging without gradient coils utilized a rotating, 45 kg, 77 mT inhomogeneous Halbach cylinder based magnet[1]. The built-in field variation of the permanent magnet array is used as a rotating spatial encoding magnetic field (rSEM). As the magnet is rotated around the sample, generalized projections onto the non-linear SEM are acquired as a spin-echo train.

To enable imaging in the 3rd direction (along the axis of the cylindrical magnet), we use the TRASE method. TRASE is a B_1^+ encoding method that requires 2 different switchable B_1^+ phase gradients (often equal and opposite) along the encoding direction[2,3]. The 1D TRASE sequence (Fig. 2) is a modified RARE spin-echo train in which the slope of the B_1^+ phase gradient switches for consecutive refocusing pulses (indicated by the + or –). The 2 phase gradients correspond to 2 k-space origins (-k$_1$ and k$_1$), and the previous k-space point is flipped across the k-space origin of the refocusing pulse to traverse k-space.

Coils: A TRASE array was designed that consists of two nested cylindrical coils (Fig. 3). Coil 1 is a short 4-turn birdcage coil (12 rungs, 18cm diam., 22cm length)[4] that produces a B_1^+ field in **Y** with a cosine shape along **X**, $B_{1y}^+(x) = |B_{1xy}^+|\cos(2\pi\, k_1 x)$. Coil 2 is a 10 turn Maxwell coil (22cm diam., 18cm length) that produces a B_1^+ field in **X** with a sine shape along **X**, $B_{1x}^+(x) = \pm|B_{1xy}^+|\sin(2\pi\, k_1 x)$. The coils are tuned to the Larmor frequency (3.29 MHz) and decoupled with a transformer (-20 dB isolation). Figure 3b, shows the relative magnitude of B_{1x} and B_{1y} from the 2 coils measured with a pick-up loop. When the two coils are driven with equal $|B_{1xy}^+|$ magnitude and spatial frequency, k$_1$, they produce the desired B_1^+ field, $B_1^+(x) = |B_{1xy}^+|e^{+i\,2\pi k_1 x}$ (uniform magnitude and linear phase). A switchable 180º phase shifter is added in the Maxwell coil RF path, which applies a sign change to every other refocusing pulse. The pulses with the phase shift thus have a negative phase gradient; $B_1(x)^+ = |B_{1xy}^+|e^{-i\,2\pi k_1 x}$.

Acquisition: The 2D rSEM method and TRASE are performed simultaneously for 3D imaging. The TRASE array must rotate with the magnet because the **Y** direction changes as the magnet rotates. For every magnet rotation, the projection onto the SEM is acquired as a TRASE-modulated 16-echo spin-echo train (each echo: readout = 196 pt, BW = 40 KHz, echo spacing = 9.7 ms). Data is acquired at 180 rotations of the magnet spaced 1º apart. Frequency-swept WURST pulses are used to achieve the same flip angle across the inhomogeneous field (BW = 25 KHz, [pw90, pw180] = [6,3] ms)[5]. The birdcage coil of the TRASE array is used as the receiver coil.

Reconstruction: **Step one** separates the echo train data along **X** to obtain 16 different **YZ**-datasets corresponding to each slice. For each of the 196 points in the readout window, the set of 16 points along the echo train populates a k-space vector (Fig. 2). The points are rearranged and FFT'ed to generate a 1D projection along **X** (Fig. 4). Only the k-space lines formed from the center points of the echos result in 1D projections that are not modulated by the B_0 SEM. This is repeated for the echo trains from each of the 181 magnet rotations. **Step two** reconstructs each set of 181 echoes (**YZ**-data) into a 2D image of the corresponding slice. The encoding matrix for each slice is calculated using 2D B_0 field maps and then iterative matrix inversion[1] is performed to separately obtain each 2D image.

RESULTS: Figure 4 shows experimental 3D imaging results using a 7.5cm thick phantom with 1.5 cm water-filled compartments spaced 3 cm apart in **X**. A 1D projection along **X** shows the water-filled compartments. Three slices are reconstructed from data at **X** = -3cm, 0cm, and 3cm using the corresponding 2D B_0 field maps.

DISCUSSION: The non-bijectivity of the SEMs results in image aliasing across the center. This is usually resolved using a surface coil array[6], but as a first step, the birdcage coil of the array was used for a receiver coil and only the reduced FOV image is shown. The blurring in the image slice is due to a combination of the spatially varying resolution of the SEMs and systematic calibration errors in our model-based reconstruction.

CONCLUSION: We demonstrate proof-of-concept 3D images in an inhomogeneous 45 kg magnet without the use of the gradient coils. TRASE encoding along **X** is ideal because like our 2D method it uses spin-echo trains, and it prevents the need for a B_0 gradient coil and GPA, which would add weight, cost, and power requirements to the portable, low-cost system. Future work will extend this 3D imaging method using larger diameter magnets and coils with the goal of portable low-cost MRI brain imaging.

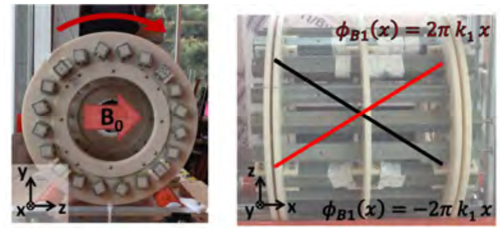

Figure 1: (a) **Y-Z** encoding is done with the rotating SEM method. (b) TRASE is done in the **X** direction using a switchable linear B_1^+ phase along **X**.

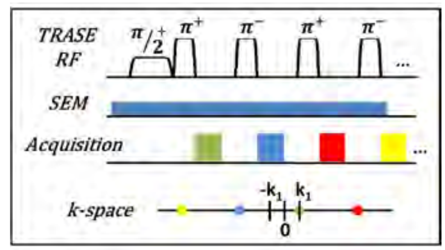

Figure 2: The TRASE sequence is repeated for every magnet rotation of the imaging sequence. The +\- indicates the sign of TRASE phase slope.

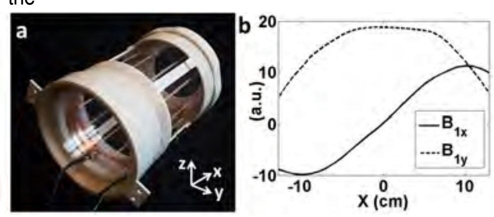

Figure 3: (a) The TRASE array is a nested birdcage and Maxwell coil. (b) The measured magnitude of B_{1x} from the Maxwell coil and B_{1y} from the birdcage coil.

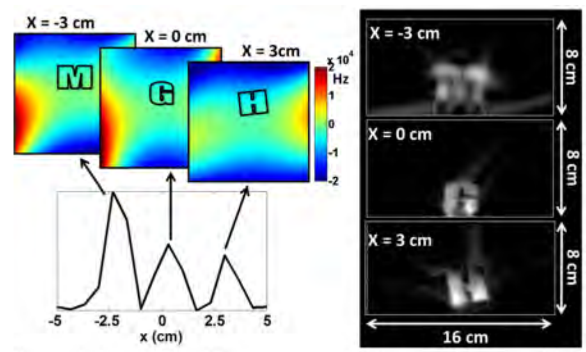

Figure 4: Image of a 3D phantom consisting of three water-filled compartments spaced 3 cm apart in X. A 1D projection along **X** for 1 rotation angle is shown (lower left). 3 image slices were reconstructed using the appropriate 2D field maps.

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