Polar Decomposition Radio-frequency Current Density Imaging With Dual-unwrapping: Simulation and Experimental Results

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INTRODUCTION

Polar Decomposition Radio-frequency Current Density Imaging (PD-RFCDI) is an imaging technique that non-invasively measures current density components inside a sample using a MRI imager [1]. However, due to the highly constrained upper limit of applied current imposed by this method, PD-RFCDI could not achieve a reasonable SNR needed for practical implementation. This work proposes a novel dual-unwrapping technique that removes these constraints on PD-RFCDI. Both simulation and experiment were used to verify this algorithm.

METHOD

Theoretically, any applied Larmor frequency current will produce a radio-frequency (RF) magnetic field $\mathbf{B}$. Under such an excitation, the magnetization $\mathbf{M}$ will rotate around an axis that is collinear with $\mathbf{B}$ at an angular speed that is proportional to the magnitude of $\mathbf{B}$. Thus the current-induced magnetic field will be translated into magnetization rotation and subsequently encoded into MRI images. Once the encoded MRI images are obtained, one is able to extract the magnetic field $\mathbf{B}$ and subsequently calculate the applied current using Ampere's law.

This is the basis of polar decomposition RFCDI which measures the current density $\mathbf{J}$ created by the applied current [1]. PD-RFCDI is able to extract the rotation information from these recorded positions of $\mathbf{M}$ to calculate the induced magnetic field $\mathbf{B}$ and hence the current density field $\mathbf{J}$. However, when the rotation angle exceeds 2π, the rotation axis can be interpreted as two possible orientations, which causes confusion in the reconstruction. To avoid such ambiguities, the earlier PD-RFCDI method required the rotation angle to be less than 2π. This posed a strong constraint on the product of the magnitude and the duration of applied current, which, in turn, significantly reduced the applicability of PD-RFCDI. In order to remove this constraint, we propose a novel dual-unwrapping algorithm to simultaneously unwrap the rotation angles and correct the falsely inverted rotation axes. We assume that the angular difference of the rotation axes between any of the two neighboring voxels are less than 0.5π. Following this assumption, an axis inversion step is applied to correct the falsely inverted rotation axes. After that, rotation angles are unwrapped using 3D quality-guided phase unwrapping [2]. This paper describes tests of the ability of this dual-unwrapping method to determine the correct magnetization rotation axis and rotation angle produced by large RF currents in the presence of inhomogeneous B_0.

SIMULATION

To test the performance of PD-RFCDI with dual phase-unwrapping algorithm, a simulation was designed with the results shown in figure 1 and 2. The range of the rotation angles is $[0, 10\pi]$, which far exceeds the constraint previously proposed. The rotation axes are set to be position-dependent. The successful reconstruction of the angle and axis maps shows that with the dual-unwrapping algorithm, PD-RFCDI is able to perform with much higher currents.

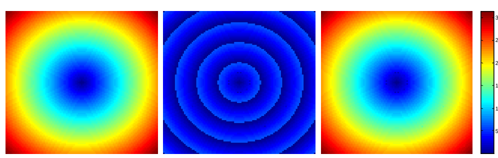

Figure1. Simulation results (rotation angle)
Right: original rotation angle image; middle: wrapped rotation angle image; left: unwrapped rotation angle image using dual-unwrap.

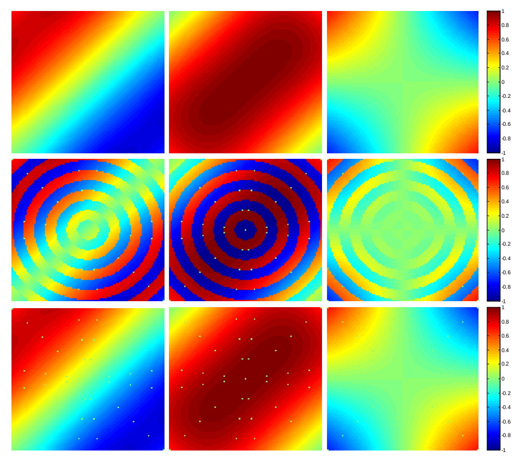

Figure 2. Simulation results (rotation axis)
Row1: x,y,z components of the original rotation axis;
Row2. x,y,z components of the wrapped rotation axis;
Row3: x,y,z components of the dual-unwrapped rotation axis

PHANTOM EXPERIMENT

The experiment was carried out on a saline-filled cylindrical phantom. The phantom was placed inside a 1.5 Tesla GE® EXCITE MR scanner. A magnetization rotation field was created in a cylindrical phantom. The rotation angle varied linearly over 4 cycles in the x direction. The axis of rotation was the +z axis. Figure 3 shows that the dual-unwrapping algorithm succeeded in recovering the angle. Figure 4 shows that the axis was recovered well except for rotations of $2k\pi$.

DISCUSSION

With the help of a novel dual-unwrapping algorithm, PD-RFCDI resolved axis and angle unwrapping simultaneously. The noise in the reconstructed simulation and experimental data is due to the unavoidable signal loss in regions where rotation angle is close to $2k\pi$.

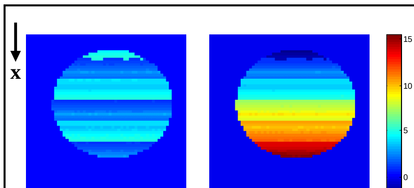

Figure 3. Reconstructed rotation axis
Left: without dual-unwrapping; right: with dual unwrapping.

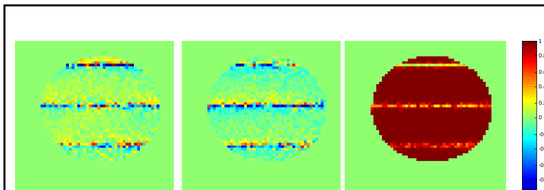

Figure 4. Reconstructed rotation axis
Left: x component; middle: y component; right: z component.

REFERENCES

[1]Greig Cameron Scott, Univ. of Toronto, 1993.
[2]Weijing Ma, Univ. of Toronto, 2004.