Susceptibility-Based Positive-Contrast MRI for Interventional Devices

Ying Dong[1], Guoxi Xie[2], and Jim Xiuquan Ji[1]

[1]*Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX, United States,* [2]*Paul C. Lauterbur Research Center for Biomedical Imaging, Chinese Academy of Sciences, Shenzhen, Guangdong, China*

INTRODUCTION

MR-compatible interventional devices, such as biopsy needles, markers, stents, and brachytherapy seeds, are often made of titanium, platinum or gold. The susceptibility of the device alters the magnetic field, which introduces fast signal dephasing and decreases the signal-to-noise ratio (SNR). As a consequence, a dark hole and bright dots due to signal shifting appear and cover an area of several times larger than the devices themselves in the MR magnitude images. Methods such as MAVRIC and co-RASOR capture the shifted signal with an off-resonance reception in their pulse sequences to create positive contrast images[1,2]. Our group has previously proposed a method based on susceptibility mapping to provide the positive contrast for brachytherapy seeds[3]. In this paper, technical advances of the method are reported on imaging of medium/larger devices such as biopsy needles on 3T systems.

THEORY

The method includes three steps: 1) image acquisition using a spin-echo sequence with a shifted 180° pulse; 2) field map calculation; and 3) form a positive contrast image by mapping the susceptibility. Unlike other susceptibility mapping methods, the proposed method uses a spin-echo sequence because it can refocus the dephasing due to the field inhomogeneity using a 180° pulse. Two sets of data are acquired with different shift-time (ΔTE) for the 180° pulse. A short echo shift can retain the phase changes due to the material susceptibility while keeping the high SNR. A phase subtraction is then used to remove the background phase before the field map is derived as

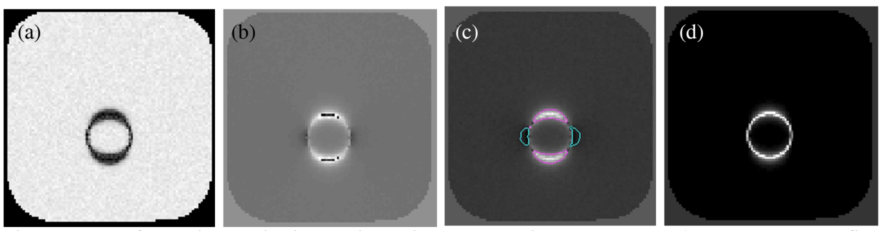

Fig.1 Images of a platinum wire in the simulation: (a) magnitude, (b) phase (ΔTE = 0.3ms), (c) field map, (d) positive contrast image by proposed method. The contour in (c) labels the +/-5ppm line.

$$\Delta \boldsymbol{B} = \Delta\Phi / (2\pi\gamma \Delta TE B_0) \qquad (1)$$

where $\Delta\mathbf{B}(\mathbf{r})$ is the normalized, susceptibility-induced field map, $\Delta\Phi$ is the phase change, γ is the gyromagnetic ratio, and B_0 is the magnetic field.

The field map can be approximated as the convolution of the susceptibility distribution with a dipole kernel[4]:

$$\Delta\mathbf{B}(\mathbf{r}) = (3\cos^2(\theta_r) - 1)/(4\pi|\mathbf{r}|^3) \otimes \chi(\mathbf{r}) \qquad (2)$$

where $\boldsymbol{\chi}(\mathbf{r})$ is the susceptibility distribution (ppm), $\mathbf{r}$ is the location of the observer, and $\boldsymbol{\theta}_\mathbf{r}$ is the azimuthal angle. Eq. (2) can be rewritten in vector-matrix form as $\boldsymbol{\psi} = \mathbf{C}\boldsymbol{\chi}$, where $\mathbf{C}$ is the convolution operator with the dipole kernel, and $\boldsymbol{\psi}$ is the field map. L_1 regularization is utilized to solve Eq. (2) by[5]

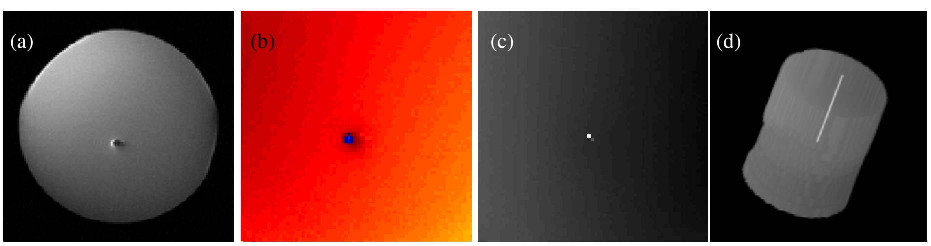

Fig. 2 Imaging a titanium biopsy needle on a 3T system: (a) magnitude image, (b) zoomed-phase image (ΔTE = 0.3ms), (c) positive contrast reconstruction by proposed method, and (d) MIP reconstruction of the needle. Note that the needle is shown as a bright structure due to its high susceptibility.

$$\min_{\chi} \|\mathbf{M}\mathbf{G}\boldsymbol{\chi}\|_1 \quad \text{subject to} \quad \|\mathbf{W}(\mathbf{C}\boldsymbol{\chi} - \boldsymbol{\psi})\| \le \varepsilon \qquad (3)$$

Here $\mathbf{M}$ is a masking matrix, $\mathbf{G}$ denotes the first order gradient operator to promote sparsity, $\mathbf{W}$ is a weighting matrix, and ε is a small constant that is determined by the noise level. The masking matrix $\mathbf{M}$ is designed to include only the useful and reliable data near the object. The object itself and a small neighboring region are masked out completely. Note that $\mathbf{M}$ can be calculated by setting an appropriate threshold to the magnitude image. The mask does not apply to the data fidelity term.

RESULTS

To test the proposed method, a computer simulation of a platinum wire was first performed with the following parameters: wire diameter = 0.55mm, length =17.3mm, FOV=70x70x10.5mm^3, matrix size =128x128x7, slice thickness =1.5mm without gap, TR = 2000ms, TE = 30ms. The echo shifts of the 180° pulse, ΔTE, was set to 0ms and 0.3ms. Reconstruction results from the simulation are shown in Fig. 1. As shown, the proposed method can produce a positive contrast image for the platinum wire, which has a much larger size than brachytherapy seeds.

Subsequently, a phantom experiment was performed on a 3T Siemens whole body MRI. The phantom consists of a titanium biopsy needle inserted into a circular container filled with water solution doped with 1mg/mL copper sulfate. The needle was put in parallel to the main magnetic field and the tip portion was imaged with FOV = 14.4x14.4x4cm^3, matrix size = 192x192x16, slice thickness = 2.5mm without gap, TR = 2000ms, TE = 15ms, and ΔTE = 0ms and 0.3ms. Acquired raw data was processed using the proposed algorithm. Fig. 2 shows the reconstruction results. Clearly the proposed method is able to provide a positive contrast image for the titanium needle which shows a much smaller object profile than the magnitude or phase images.

CONCLUSION

Advances were reported on a novel method that can provides positive-contrast images of interventional devices. The method works by directly mapping the material susceptibility. Simulations and experimental results show the feasibility of the method for imaging medium/large devices such as biopsy needles. This approach has the potential to enhance the visualization and localization of the devices, thus improve the effectiveness of interventional MRI.

REFERENCES

1. K.M. Koch et.al, MRM 2009
2. P.R. Seevinck et.al, MRM 2011
3. Y. Dong et. al, MRM 2014
4. J. D. Jackson et. al, American Journal of Physics, 1999
5. J. Liu et.al, NeuroImage, 2012