Susceptibility-Based Positive-Contrast MRI for Brachytherapy Seed Identification

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INTRODUCTION

Brachytherapy treats cancer by directly inserting radioactive seeds into the tissues to locally kill malignant cells. MRI has been proposed as a potential imaging method for surgery planning, visual assistance, and treatment evaluation in this procedure. However, brachytherapy seeds and the surrounding tissues normally show as enlarged dark spots, which make it difficult to differentiate from the cavities/voids in the tissues and to identify and to localize the seeds. Many efforts have been proposed to provide positive contrast. These include new pulse sequences, such as a 3D center-out radial sampling with off-resonance reception[1] and inversion-recovery with ON-resonant water suppression[2], and post processing methods, such as susceptibility gradient mapping (SGM)[3] and SGM with original resolution (SUMO)[4] among others. These methods generally produce highlighted "rings" around the seeds or shift the signals from surrounding tissues to the seed locations. In this paper, we propose a method based on direct susceptibility mapping. Since the seeds themselves have high susceptibility, seed identification and localization are more straightforward and accurate.

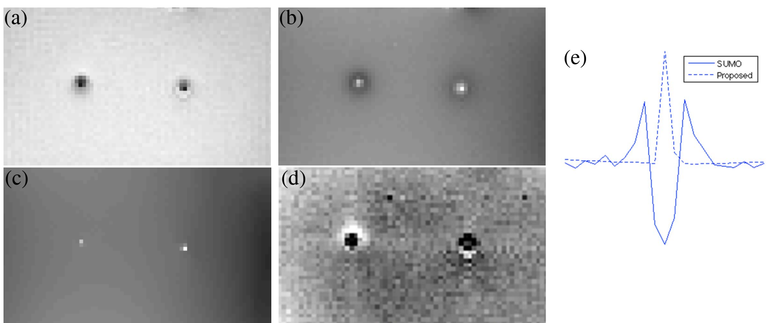

Fig.1 (a) magnitude, (b) field map, (c) positive contrast by proposed method, (d) positive contrast by SUMO method, and (e) comparison of location width.

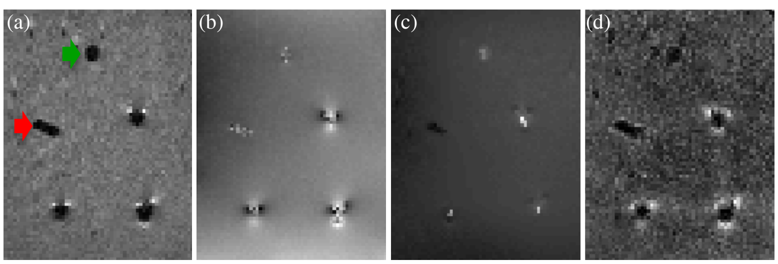

Fig. 2 (a) magnitude, (b) field map, (c) susceptibility map using proposed method, and (d) SUMO method. Images are cropped for better visualization.

THEORY

In MRI, the induced local magnetic field can be approximated as the convolution of the susceptibility distribution with a kernel, which is the response of a dipole[5]:

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

where $\Delta\mathbf{B}(\mathbf{r})$ is the susceptibility-induced field change (ppm), $\chi(\mathbf{r})$ is the susceptibility distribution (ppm), $\mathbf{r}$ is the location of the observer (cm), and $\boldsymbol{\theta}_r$ is the azimuthal angle. Eq. (1) 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. Obtaining susceptibility directly by solving this equation is difficult due to singularity and ill conditions. However, since the number of pixels representing the brachytherapy seeds is small, the seed images can be considered sparse. Therefore, L_1 minimization is appropriate for solving the problem, as shown in[6]

$$\min_{\chi}\|\mathbf{G}\boldsymbol{\chi}\|_1 \text{ subject to } \|\mathbf{M}(\mathbf{C}\boldsymbol{\chi} - \boldsymbol{\psi})\|_2 \le \varepsilon \quad (2)$$

Here $\mathbf{G}$ denotes the first order gradient operator to promote sparsity, $\mathbf{M}$ is a weighting matix, and ε is a small constant that is determined by the noise level. A unique problem in the application is that the size of the seeds is usually comparable to the size of the image voxel. As a result, in order to apply Eq. (2), special cares must be taken: (1) in the proposed method, the weighting matrix $\mathbf{M}$ is binary, designed to include only the useful and reliable data near the seed. The seed itself and a small neighboring region are masked out completely. (2) Spin-echo sequences with two shifted echo times are used to derive $\Delta\mathbf{B}(\mathbf{r})$ which results in less signal loss and less geometric distortion in areas near the seeds (unlike the gradient-echo type sequences commonly used in conventional susceptibility mapping). Note that $\mathbf{M}$ can be calculated by setting an appropriate threshold to the magnitude image; the mask does not apply to the sparsity term in the proposed formulation.

RESULTS

Two experimental datasets were acquired: the first was from a gel phantom (with two STM 1251 seeds inserted) and the second from a phantom made of porcine meat (with three STM 1251 seeds inserted). Both datasets were acquired on a 4.7T, 33cm-bore Varian MR system using the modified spin echo sequence. The echo shifts of the 180° pulse, ΔTE, were set to -0.3ms, 0ms, and 0.3ms in both datasets. In both experiments, images were acquired for cases where the seeds are parallel, or orthogonal, to the main magnetic field. In addition, to test the capability of the proposed method in differentiating the seeds from other susceptible structures such as air-tissue boundary, a plastic stick (red arrow in Fig. 2) and a bamboo stick (green arrow in Fig. 2) were also inserted in the porcine meat phantom together with the seeds. Acquisition parameters in both experiments were: field of view $80\text{x}80\text{x}10.5\text{mm}^3$, matrix size 128x128x7, TR=1000ms, and TE=30ms (nominal). The field maps were calculated using the phase images, by the relationship $\Delta\mathbf{B} = \Delta\Phi/(2\pi\gamma\Delta TEB_0)$, where $\Delta\Phi$ is the phase change, γ is the gyromagnetic ratio, and B_0 is the magnetic field. The positive contrast images by the SUMO method were produced for comparisons.

Fig. 1 shows that the proposed method can produce a positive contrast image where seeds have a much smaller profile. Results in Fig. 2 further show that the proposed method can differentiate the seeds from the plastic and bamboo sticks, which have smaller susceptibility. In both experiments, the proposed method results in smaller seed profiles and therefore more accurate seed localization.

CONCLUSION

A new method is developed to generate positive contrast and to identify brachytherapy seeds by directly mapping their susceptibility. This is the first attempt to apply the similar technology to brachytherapy seed imaging. Preliminary experimental results indicate that the proposed method is feasible, even the seeds are much larger than conventional sources in susceptibility mapping (such as SPIO particles).

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