MRI Based Electrical Impedance Imaging of Tumors with Iterated Sensitivity Reconstruction Using Regularization

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Purpose

Several researchers have demonstrated that the electrical properties, specifically the impedance of malignant tissues is significantly different from those of normal and benign tissues [Malich *et al, Clin.Rad.*,56:278-283, 2001; Silva *et al. Med. Biol. Eng. and Comp.*, 38:26-30, 2000]. Therefore, *in vivo* impedance imaging of suspicious lesions could aid in improving the sensitivity and specificity of detecting malignant tumors. MRI based impedance imaging is a novel method, in which weak electrical currents are injected into the tissue and the resulting perturbations in magnetic field were measured using phase information in MR images. We have reported our preliminary studies with phantoms as well as some *in vivo* experiments. However, in those studies, reconstruction was done with the non-iterative sensitivity matrix approach, which assumed a linear relationship between the measured field perturbations and relative conductivity distribution. For large conductivity variations, this linearity assumption failed and the resulting images underestimated the conductivity variations. This resulted in poorer spatial specificity and sensitivity. We refined our reconstruction technique with an iterative approach to account for the nonlinearities. The goal is to verify potential of MR-EIT to aid in the diagnosis of tumors.

Methods

When a sinusoidal current is injected into an object, the z-component of the resulting magnetic fields induce additional phase information in MR images. A modified spin-echo sequence was used, where several π pulses were applied during the zero-crossings of the sinusoidal current (Fig.1) [Mikac *et al, MRI 19: 845 856 (2001)*]. This phase shift accumulates across these π pulses and is given in the final image as $\varphi(\mathbf{r}) = 4\cdot\gamma\cdot N\cdot b_z(\mathbf{r}) / \omega$, where γ is the gyromagnetic ratio, N the number of cycles of injected current, $b_z(\mathbf{r})$ the amplitude of z-component of current-generated magnetic field at point $\mathbf{r}$, and ω the angular frequency of the injected current. Therefore, once the phase, $\varphi(\mathbf{r})$ is measured, $b_z(\mathbf{r})$ can be calculated. In the original approach, a linear approximation $\Delta B(\mathbf{r}) = S(\mathbf{r},\mathbf{r}')\,\Delta\sigma(\mathbf{r}')$ was assumed to reconstruct conductivity image. Here $\Delta B(\mathbf{r})$ is the change in magnetic field at point $\mathbf{r}$ for a given current injection scheme resulting from a change $\Delta\sigma(\mathbf{r}')$ in the conductivity at point $\mathbf{r}'$. S is calculated using Finite Element Method (FEM). Recently, we have adopted an iterative reconstruction with Tikhonov regularization, which improved the accuracy as well as spatial specificity of the MREIT images. Details of this method and its assessment with phantom studies were presented in another manuscript that is being submitted concurrently. In summary, the matrix equation was modified with the addition of a *regularization parameter*, λ, and became $(\mathbf{S^T\Delta B = (S^TS+\lambda I)\,\Delta\sigma})$, where **I** is the identity matrix. This equation was solved for different values of λ using conjugate gradient method and the optimum value of λ was found. The conductivity distribution that is calculated after each iteration was assigned as the initial value for the next iteration and the iterations are repeated until the difference between the results of two consecutive iterations are below a predefined threshold. Current was injected from four electrodes placed across the animal's body and six different current distributions were generated by using different combinations of electrode pairs. This scheme also improved the uniformity and sensitivity of the MREIT images.

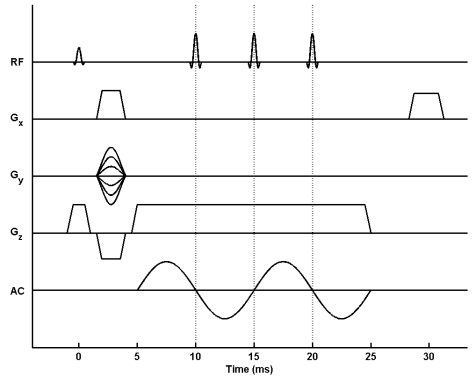

Fig. 1. Pulse sequence used in MR-EIT

Results

Data were collected in a whole body 4T MRI system with a MRRS console. Two rats were imaged, which were bearing malignant tumors induced by the carcinogen ENU. Animals were anesthetized prior to imaging. All procedures were approved by the IACUC. Structural images were collected using SE sequence prior to MREIT images. The data matrix was 128X128, FOV = 10cm, slice thickness = 4mm, with 2mm gap. TR = 3s, TE = 50ms and NEX = 2 were used. MREIT images were collected using the previously outlined pulse sequence with TR=500ms, TE=30ms, and NEX=12, 64X64 data matrix, FOV = 10cm, slice thickness = 4mm with 2mm gap. 2 cycles of 100Hz current with 2mA rms was applied through different pairs of four electrodes. The resulting images clearly show the higher conductivity regions. Especially in animal-1, higher conductivity map of the tumor precisely overlaps with the one seen in the structural image. The mean conductivity in the tumor region was 2.8 times higher than the mean conductivity in the rest of the body for animal-1.

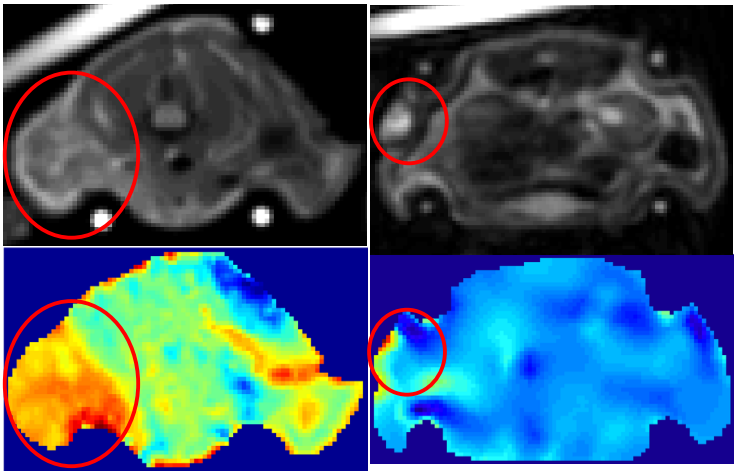

Fig.2. Structural (top) and MREIT (bottom) images of two animals. Left and right columns show the images of animal-1 and animal-2, respectively. Tumor areas are circled with red lines. Bright objects outside the animals were markers to identify exact location of electrodes.

Discussion

In this study, it has been demonstrated that MRI based impedance imaging has the potential to investigate malignant tumors *in vivo*. Improvements in current injection and utilization of iterative reconstruction with regularization significantly improved the accuracy and spatial specificity of MREIT. In our experiments it was also observed that precise localization of electrode placement was critical to define boundary conditions accurately, which in turn affected the quality of MREIT images. In the presented study, 2D FEM formulation was used. Currently 3D FEM is being developed to improve the accuracy of MREIT images further.

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