Simulation of MREIT using Balanced Steady State Free Precession (b-SSFP) Pulse Sequence

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Abstract. Magnetic resonance electrical impedance tomography (MREIT) utilizes the relation between conductivity and magnetic flux density induced by externally injected current to perform conductivity imaging of body tissues. A spin echo pulse sequence has been predominantly used in MREIT to acquire the $z$-component $B_z$ of the induced magnetic flux density data from MR phase images. Spin echo based MREIT pulse sequences are most stable and successful in producing high-resolution conductivity images in postmortem and in vivo animal and human experiments. In some applications, localization of a physiological event is desirable. Examples may include detection of neural activities through conductivity changes. In such a case, it would be necessary to maximize the sensitivity. In this paper, we suggest using a balanced steady state free precession (b-SSFP) pulse sequence to localize a small conductivity change. The induced magnetic flux density $B_z$ subject to an injection current makes an off-resonance phase in b-SSFP signals. We expect the high sensitivity of b-SSFP signals to any off-resonance phase change will be advantageous for detecting a small conductivity change. Using computer simulations, we show the feasibility of functional or time-difference MREIT using the b-SSFP pulse sequence.

1. Introduction

We perform conductivity imaging of an electrically conducting object in magnetic resonance electrical impedance tomography (MREIT). Injecting current into the object, it produces a distribution of an internal magnetic flux density $\mathbf{B} = (B_x, B_y, B_z)$. Using an MRI scanner with its main field in the $z$ direction, we can obtain an image of $B_z$ from MR phase data. The current injection must be done in synchronous with an adopted pulse sequence to properly accumulate $B_z$ data in MR phase images. We can reconstruct a conductivity image of the object from multiple $B_z$ data subject to multiple injection currents at different directions based on the relation between conductivity and $B_z$.

Studies in neurophysiology have detected about 2 to 5 % changes in conductivity values of neural tissues during neuronal activities [1]. The primary goal of this paper is to test the feasibility of detecting such a small conductivity change using MREIT. It would require fast data acquisitions and a high signal sensitivity to current injection. Balanced steady state free precession (b-SSFP) pulse sequence has been known for its high signal-to-noise ratio (SNR) per unit time and high sensitivity to any off-resonance phase. We have recently proposed its use in MREIT as an alternative to conventional spin echo based pulse sequences [2]. The phase change due to the induced $B_z$ signal subject to a current injection during a time interval of $T_c$...
Figure 1. Cross-sections of a cylindrical domain with an anomaly at the center. (a) True MR magnitude image assuming the same proton density for both the anomaly and background. (b) True conductivity image with 5% conductivity contrast between the anomaly and background.

contributes to an extra off-resonance phase in b-SSFP signals. Since this will allow higher signal changes, we propose the b-SSFP in time-difference or functional MREIT.

In this study, we performed numerical simulations of the b-SSFP to test its feasibility in MREIT to detect 5% conductivity contrast. In previous MREIT studies, we have used only MR phase images to extract $B_z$ data. Adopting the b-SSFP pulse sequence, we will investigate both MR magnitude and phase images since induced $B_z$ data affect both of them in b-SSFP. We will propose utilizing the b-SSFP pulse sequence to further explore the feasibility of time-difference or functional MREIT as a new method in neuroimaging.

2. Methods

2.1. b-SSFP Signals

Right after a 90° RF pulse in the b-SSFP pulse sequence, $x$ and $y$ components of a transverse magnetization are given by

$$M_y(\theta) = M_0(1 - E_1)\sin(1 - E_2 \cos \theta)/d$$

$$M_x(\theta) = M_0(1 - E_1)\sin \alpha E_2 \sin \theta/d$$

$$d = (1 - E_1 \cos \alpha)(1 - E_2 \cos \theta) - E_2(E_1 - \cos \alpha)(E_2 - \cos \theta)$$

where $E_1 = e^{-T_R/T_1}$ and $E_2 = e^{-T_R/T_2}$ [3], $T_R$ is the repetition time, $\theta$ the off-resonance phase, $M_0$ the proton density and $\alpha$ is the flip angle. If we position the data acquisition window at the center of the pulsing period, the phase of the b-SSFP signal is given by

$$\phi(\theta) = \tan^{-1}(M_x/M_y) = \tan^{-1} \left( \frac{E_2 \sin \theta}{1 - E_2 \cos \theta} \right) + \frac{\theta}{2}$$

where $\theta = \gamma \Delta BT_R$. Injecting current for a duration of $T_c$ in a pulsing period generates a $z$-component of a magnetic flux density $B_z$, which contributes to the off-resonance phase $\theta$ as

$$\theta = \gamma \Delta BT_R + \int_0^{T_c} \gamma B_z dt = \gamma \Delta BT_R + \gamma B_z T_c$$

where $\Delta B$ is the main field inhomogeneity and $\gamma$ is the gyromagnetic ratio of hydrogen.

2.2. Numerical Simulation

We constructed a three-dimensional cylinder model with 120 mm diameter and 100 mm height and placed a cylindrical anomaly of 36 mm diameter and 30 mm height at its center. The anomaly and background conductivities were 0.105 S/m and 0.1 S/m respectively to simulate 5% conductivity contrast. Figure 1 shows the MR magnitude (for $\theta = 0$) and conductivity image of the cylindrical model with the anomaly. We attached four equally spaced electrodes
Figure 2. Simulated images using the b-SSFP for the horizontal current injection. (a) and (b) are MR magnitude images without and with the anomaly, respectively. (c) and (d) are corresponding MR phase images. (e) is the difference between (b) and (a). (f) is a scaled version of (e) to express percentile changes. (g) is the difference between (c) and (d). (h) is a scaled version of (g) to express percentile changes.

of size $80 \times 80 \times 5 \text{ mm}^3$ around the cylindrical model. Imaging currents of 5 mA amplitude were injected horizontally and vertically between two opposing pairs of electrodes. The average current density underneath each electrode was $0.78 \text{ A/m}^2$. We first computed $B_z$ images over a grid of $128 \times 128$ for both imaging currents using the three-dimensional MREIT forward solver implemented in COMSOL (Comsol AB, Burlington MA, USA). MR phase changes determined by these $B_z$ data were plugged into the b-SSFP equations as the off-resonance phase term. Using the b-SSPF equations for MREIT described in section 2.1, we computed both MR magnitude and phase images. We assumed that $T_R = 70 \text{ ms}$ and $T_c = 63 \text{ ms}$. We validated the numerical simulation method by checking various cases of known results.

3. Results

Figure 2 shows the results for the horizontal current injection in the middle slice of the cylindrical domain. MR magnitude images in figure 2(a) and (b) are from the model without and with the anomaly, respectively. These b-SSFP images are different from the true MR magnitude image in figure 1(a) since they include the effects of the off-resonance phase due to the injection current. Figure 2(e) shows the difference between two MR magnitude images in (b) and (a). Figure 2(f) is the same difference image expressed in percentile changes. We can see that the maximal change in the MR magnitude image is about 0.2% near edges of current injection electrodes where we have the largest phase change. Around the anomaly, the magnitude image change is about 0.05%. We note that the horizontal imaging current produces negligible changes in the MR magnitude image in a horizontal band at the center. Figure 2 (c) and (d) show two phase images in the middle imaging slice without and with the anomaly, respectively. Figure 2 (g) is the difference image between (d) and (c). Figure 2 (h) is the same difference image expressed in percentile changes. We found that the change in MR phase image around the anomaly region is about 8% or 0.46°. We note that the horizontal imaging current visualizes distinct phase changes along the horizontal (tangential) direction of the anomaly. Figure 3 shows the numerical simulation results for the case of vertical imaging current with similar interpretation.
Figure 3. Simulated images using the b-SSFP for the vertical current injection. (a) and (b) are MR magnitude images without and with the anomaly, respectively. (c) and (d) are corresponding MR phase images. (e) is the difference between (b) and (a). (f) is a scaled version of (e) to express percentile changes. (g) is the difference between (c) and (d). (h) is a scaled version of (g) to express percentile changes.

4. Discussion and Conclusion
The edge effects appear prominent in figures 2 and 3. We may significantly reduce the edge effects since it is possible to design an electrode with almost uniform current density underneath it [4]. We may also reduce numerical errors around surface electrodes by using a finer mesh. By properly choosing the electrode size, the average current density of 0.78 A/m^2 underneath each electrode was kept lower than the estimated threshold value of 1.2 A/m^2 to stimulate a neuron. The anomaly is visible in a better way when we scaled the changes from absolute to percentile values. This scaling removes the sign in absolute phase changes and compensate effects of spatial variation in phase.

The fundamental requirement in functional MREIT is whether we can detect small conductivity changes with imaging current small enough not to stimulate a neuron. Numerical simulations described in this paper are encouraging for a successful detection of endogenous neural activities by using functional MREIT (fMREIT) or time-difference MREIT (tdMREIT). We propose b-SSFP based pulse sequences to perform functional imaging in MREIT.

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References
[1] Meister M, Pine J and Baylor D A 1994 Multi-neuronal signals from the retina: acquisition and analysis J. Neurosci. Meth. 51 95-106
[2] Minhas A S, Woo E J and Lee S Y 2009 Magnetic flux density measurement with balanced steady state free precession pulse sequence for MREIT: computer simulation study Proc. IEEE EMBC09 (Minneapolis, MN, USA) 2276-8
[3] Zur Y, Stokar S and Bendel B 1988 An analysis of fast imaging sequences with steady-state transverse magnetization refocusing Mag. Reson. Med. 6 175-193
[4] Ksienski D A 1992 A minimum profile uniform current density electrode IEEE Trans. Biomed. Eng. 39 682-92