Bz-SNR-Enhanced Echo-Shifted Incoherent Steady State Imaging for Electrical Conductivity Mapping

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Introduction: Electrical conductivity in biological tissues varies depending on their physiological and pathological conditions, potentially providing valuable diagnostic information. Magnetic resonance electrical impedance tomography (MREIT) (1) was recently introduced to achieve high spatial resolution, wherein the internal magnetic flux density (B_z) induced by current injection results from image phases and electrical conductivity is then calculated using the harmonic B_z algorithm (2). To achieve accurate conductivity distribution in tissues, a high signal-to-noise ratio (SNR) in B_z is critical, which is proportional to the product of current injection time (TC) and SNR in magnitude image (3). To effectively enhance the SNR of B_z in MREIT and speed up data acquisition, in this work we develop a B_z-SNR-optimized echo-shifted incoherent steady state imaging pulse sequence for accurate quantification of electrical conductivity, wherein free induction decay (FID) signals experience multiple current injections to form an echo without apparent loss of signals while retaining high imaging efficiency.

Materials and Methods: A schematic of the proposed, multi-slice interleaving echo-shifted incoherent steady state imaging pulse sequence (based on spoiled gradient recalled echo similar to (4,5)) with alternating current injection for each slice is shown in Fig. 1. Echo shifting in a multi-slice interleaving fashion is adopted to increase TR and thus enhance SNR in magnitude image. The number of echo shifting (NES) is adjusted by properly positioning additional spoiler gradient pulses and effectively increasing the time of echo (TE_{eff}). Current with positive and negative polarities is injected in an alternating fashion for each slice to remove background phases and extract only current induced image phases. Since in the proposed, echo shifted incoherent steady state pulse sequence FID signals experience multiple current injections (depending on NES) to form an echo, the effective current injection time (TC_{eff}) is correspondingly increased (directly proportional to NES), resulting in a high SNR in B_z (SNR_{Bz}) while retaining imaging efficiency. To investigate an optimal NES for SNR_{Bz}, numerical simulations were performed using the following three steps: 1) Given the current amplitude, B_z is calculated by the Biot-Savart law using a cylindrical homogeneous model, assuming that a pair of electrodes cover the whole area in both the end cross sections of the model, 2) Transverse magnetizations (M_{xy}) are calculated using the Bloch equation, assuming that the current-induced magnetic field inhomogeneity produces Lorentzian spectral distribution, and 3) Apparent SNR_{Bz} is estimated as: $\mathrm{SNR_{Bz}} = \sqrt{2}\gamma TC_{eff}\Gamma_M$, where γ is the gyromagnetic ratio and Γ_M is the SNR in magnitude image. Phantom experiments were performed on a 3T (Magnetom Trio, Siemens Medical Solutions, Erlangen, Germany) using the proposed, multi-slice echo-shifted incoherent steady state imaging pulse sequence with increasing NES from 0 to 3 to investigate the effect of NES on both the SNR in B_z and the accuracy of reconstructed conductivity. A cylindrical phantom was used that consists of two cylindrical agar gel objects (2.79 S/m and 1.14 S/m, respectively) and a background saline solution (0.12 S/m). Current injection was applied in two orthogonal directions with an amplitude of 10/-10mA and a TC of 6ms (Fig. 1). The imaging parameters were: TR, 72ms; TE, 4ms; flip angle, 15°; slices, 8; FOV, 150mm^2; thickness, 4mm; in-plane matrix, 128x128; average, 20; imaging time: 3mins for each direction. After multi-coil image combination, B_z was extracted and then conductivity map was reconstructed by the harmonic B_z algorithm (2) using CoReHA software package (6).

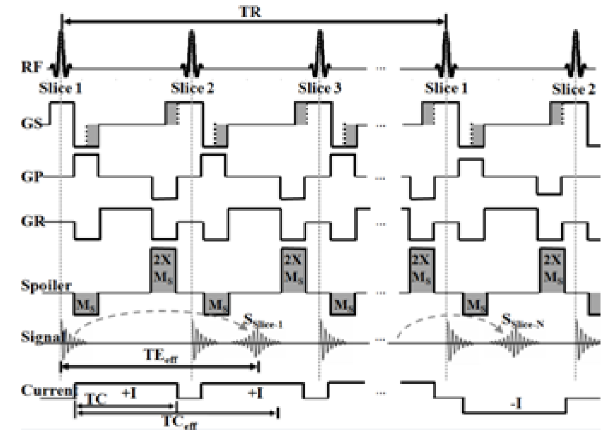

Fig. 1. A timing diagram of the proposed ES-GRE imaging method for one echo-shifting and TR-interleaved current injection scheme in MREIT experiment

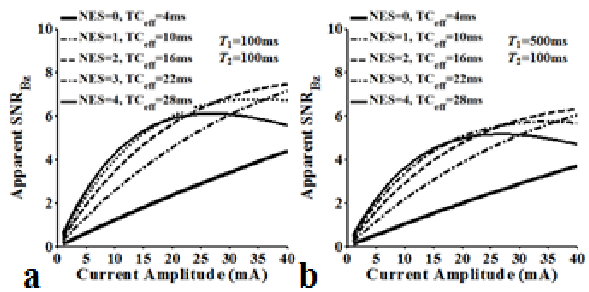

Fig. 2. Apparent SNR_{Bz} calculated numerically for different number of echo-shifting with varying amplitude of injected current in two different tissues.

Results and Conclusion: Figure 2 shows the numerically simulated apparent SNR_{Bz} for a range of NES and current amplitudes. For the two different tissues (T_1=T_2=100ms and T_1=500 and T_2=100ms), the apparent SNR_{Bz}, if given the NES, rises with increasing current amplitude up to a certain value and then decreases, while in a range of low current amplitudes (1-15 mA) it becomes saturated with increasing NES. Note that large current amplitude and long current injection do not necessarily guarantee high SNR_{Bz} and accurate conductivity reconstruction. Fig. 3 shows image comparison in the proposed method with increasing NES as compared with the reference (spin echo conductivity imaging). As expected in Fig. 2, SNR_{Bz} increases with increasing NES. Particularly at NES=3, conductivity contrast among the three materials are comparable to that in the reference while imaging speed in the proposed method is over four-fold. In conclusion, the proposed, multi-slice echo-shifted incoherent steady state imaging with alternating current injection for each slice is a promising strategy for enhancing SNR_{Bz} and reconstructing accurate conductivity with high imaging efficiency.

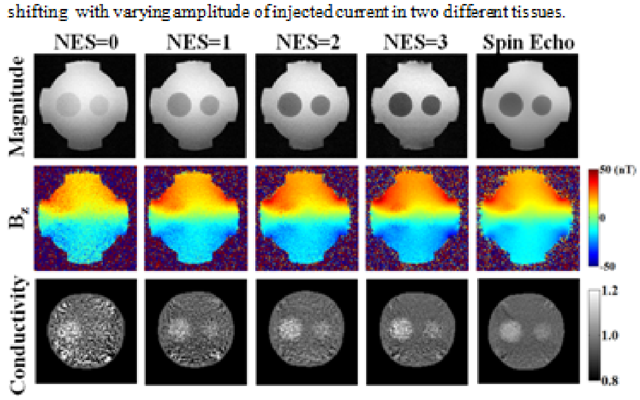

Fig. 3. For each value of NES (0 to 3), acquired MR magnitude images (first row), estimated B_z (second row), and reconstructed conductivity images (last row). Those acquired using spin echo imaging is given in the last column as a reference.

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