Correction of stray magnetic fields caused by cable currents is essential for human in-vivo brain magnetic resonance current density imaging (MRCDI)

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Introduction: Accurate mapping of current flows in the human brain is important for many neuroscientific applications. MRCDI is an emerging method, which combines MRI with externally applied alternating currents to derive current flow distributions based on measurements of the current-induced magnetic fields. However, inaccurate and inconsistent measurements occur unless the stray magnetic fields caused by the currents flowing in the feeding cables are corrected [1]. Here, we explore the influences of the stray magnetic fields due to the cable-currents in realistic experimental MRCDI set-ups.

Theory and Methods: Alternating electrical currents in synchrony with the MR sequence are generated by a current source, filtered to avoid RF interference, and injected into the human head via scalp electrodes (Fig. 1). The injected currents create a magnetic field distribution, and the field component $\Delta B_{z,c}$ that is parallel to the scanner field modulates the measured MR signal phase accordingly. The measured phase difference for opposite currents can thus be used for current-induced field $\Delta B_{z,c} = (\sphericalangle\mu^+ - \sphericalangle\mu^-)/m_{seq}$ calculations, where m_{seq} is the phase sensitivity of the sequence that can be simulated by Bloch equations and rotation matrices [1,2]. The measured $\Delta B_{z,c}$ can then be used for current flow reconstructions $J_{rec} = J_0 + \frac{1}{\mu_0}\left(\frac{\partial(\Delta B_{z,c} - \Delta B_{z,c}{}^0)}{\partial y}, -\frac{\partial(\Delta B_{z,c} - \Delta B_{z,c}{}^0)}{\partial x}, 0\right)$, where $\Delta B_{z,c}{}^0$ and J_0 are the magnetic field and current flow simulations for a uniform conductivity distribution [3]. Recently, we have achieved consistent $\Delta B_{z,c}$ measurements in the human brain with 0.1nT sensitivity (Fig. 2; for a total scan time of ~9 mins) by means of an optimized sequence (Fig. 1b), including a correction for the stray magnetic fields of the cables. Here, we explore the importance of correcting these fields for MRCDI measurements for a range of cable configurations.

We performed Biot-Savart simulations to observe the field changes due to wire segments that are orthogonal to the scanner field and placed d = [4–16] cm away, and due to a misalignment by θ = [0–40] degrees of the cable segments that are ideally parallel to the scanner field (Fig. 3). The field change simulations were performed to imitate stray fields in an MRCDI experiment for Ic = 1 mA currents. Here, we use the current-induced field simulations based on the realistic head model of the first subject in [1], and reconstruct the current flows from the sum of simulated relevant and stray current-induced fields, and from the relevant fields only, to demonstrate the deviations for various realistic d and θ values.

Results: Figure 2 shows the recently achieved unambiguous $\Delta B_{z,c}$ measurements with 0.1 nT sensitivity, and corresponding current flow reconstructions. The reconstruction method does not preserve sharp changes occurring e.g. in sulci, but it still performs well in preserving higher currents in well-conductive regions, e.g. along the longitudinal fissure.

Biot-Savart simulations (Fig. 4) demonstrate that the current-induced fields with stray fields for d<12 cm severely deviate from the ideal situation (d→ ∞; first row and first column). A misalignment angle θ_y in the y-z plane influences the stray fields similar to the distant wire case: R^2 drastically drops to near zero for $\theta_y = 15°$. A misalignment angle θ_x in the x-z plane causes the stray field to shift spatially in the x-direction. Even a small misalignment of θ_x ~10° can cause severe stray fields with a more than 20% drop in R^2.

Current flow simulations (Figure 5) show no significant loss in reconstruction accuracy for d >8 cm. However, R^2 drops drastically for d < 8 cm, and erroneously high current density estimates appear in the entire region between the electrodes (red dashed rectangle). Cable misalignment mostly influences the field estimates near electrodes and causes misestimation of the tissue currents. Significant drops in R^2 (>10%) occur for misalignments more than 20° for d = 16 cm.

Discussion and Conclusion: Field deviations that exceed the so far best demonstrated sensitivity level of 0.1 nT in vivo (corrected measurements, [1]) can occur due to a 17 cm long wire placed as far

as 20 cm away from the region of interest, or due to a slight cable misalignment of θ >3°. In an example that mimics a realistic experimental set-up with d = 12 cm, θ_x =10° and θ_y =20°, current flows are misestimated approximately 45% near electrodes and 10% in inner brain regions, which demonstrates the need for correction.

References: [1] Göksu et al, Neuroimage 2018;171:26–39. [2] Jaynes et al, Phys Rev 1955;98:1099–105. [3] Park et al, Phys Med Biol 2007;52:3001–13.
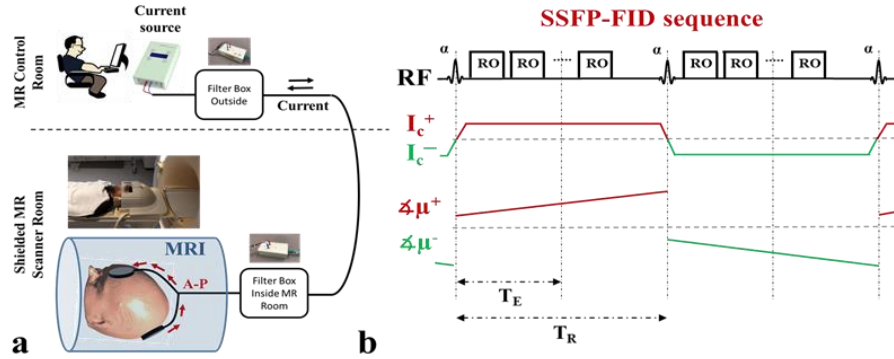
Figures

Figure 1. (a) Experimental set-up for MRCDI. (b) Schematic diagram of the MRCDI method based on steady-state free precession free induction decay sequence.
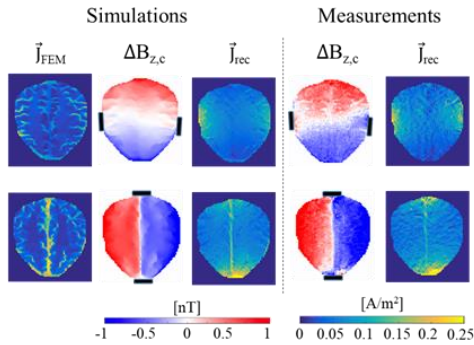

Figure 2. MRCDI results in [2] for two different current injection profiles (Right-Left at top and Anterior-Posterior at bottom). Current flow simulations based on finite element method $\vec{J}_{FEM}$ is used to simulate $\Delta B_{z,c}$, and $\Delta B_{z,c}$ simulations and measurements are used to reconstruct currents $\vec{J}_{rec}$.
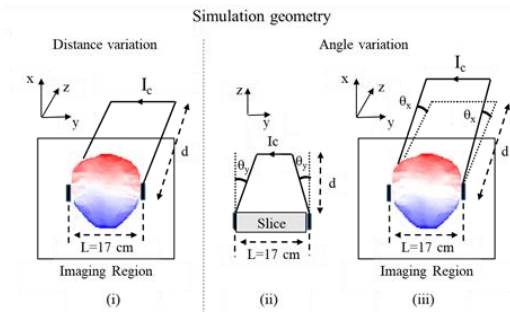

Figure 3. Simulation set-ups for cable-current-induced stray fields. The simulations were performed for a realistic head of width L = 17 cm. Distance variation: (i) A wire segment 17 cm in length placed distance d away from the imaging region. The connecting cables closing the loop are placed parallel to the scanner's field (z-direction), and thus do not contribute to the measurable field. Angle variation: The connecting cables are misaligned (ii) angle θ_y in the y-direction or (iii) angle θ_x in the x-direction.
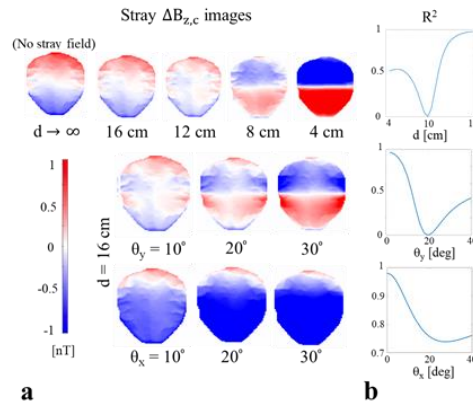

Figure 4. Biot-Savart simulations of the cable-current-induced stray fields. (a) The desired $\Delta B_{z,c}$ image without stray fields (left) is compared with $\Delta B_{z,c}$ images with stray fields for four different simulations in which the wire segment is placed d = [4, 8, 12, 16] cm away from the imaging region (first row). $\Delta B_{z,c}$ images for cable misalignments θ_y = [10, 20, 30] degrees in y-direction (second row) and θ_x = [10, 20, 30] degrees in x-direction (third row). Simulations were performed for d = 16 cm. (b) The coefficients of determination between the stray magnetic fields and the desired $\Delta B_{z,c}$ image without stray fields.
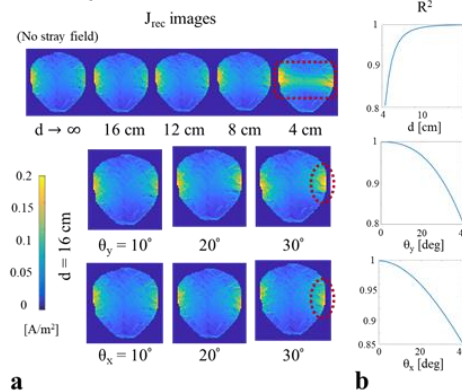

Figure 5. Projected current density images J_{rec} reconstructed from the Biot-Savart simulations in Figure 4.