Imaging electric conductivity and conductivity anisotropy via eddy currents induced by pulsed field gradients

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PURPOSE: The capacity to measure conductivity and conductivity anisotropy in vivo and non-invasively has practical significance in a number of biomedical applications. For example, large changes of tissue conductivity have been reported in tumors, strokes and myocardial infarction. Considerable early efforts were focused on the measurement of injected low-frequency currents (1-3). Electric properties tomography (EPT), on the other hand, maps electric properties based on the interaction of B1 field with tissues (4-6). While current-injection methods typically operate at a frequency below 0.5 MHz, EPT methods based on B1 field measure conductivity at the Larmor frequency (typically 100s MHz). Here, the potential of measuring "DC" conductivity and conductivity tensor based on eddy currents induced by the switching of imaging gradients is investigated both theoretically and experimentally. As the gradient directions can be readily controlled, various components of the conductivity tensor can be assessed. Simulation, phantom and in vivo human experiments were conducted to demonstrate the feasibility. The method described here provides a strategy for in vivo imaging of "DC" or low-frequency tissue conductivity non-invasively with MRI.
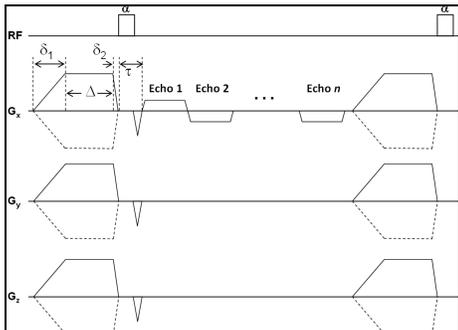

Fig. 1. Pulse sequence for generating and measuring eddy currents by pulsed field gradients. The sequence is repeated with reversed gradient polarity.
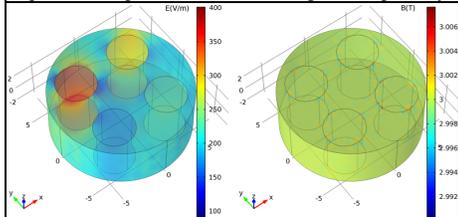

Fig. 2. Electrical (left) and magnetic (right) field generated in the phantom by gradient switching, calculated by finite element simulation.

METHODS: Switching of a pulsed field gradient induces a temporally varying magnetic field. According to Faraday's law, a changing magnetic field creates an electric field. In a conductive medium such as biologic tissues, this electric field leads to electric currents called eddy currents. In turn, the eddy current induces a small magnetic field perturbation to compensate the switching of the pulsed gradient. This eddy-current induced field is measurable from the phase of MRI images (Fig. 1). Once the field is measured, the underlying eddy current and tissue conductivity can be solved based on Maxwell's equations.

A numerical phantom was simulated, consisting of 4 parallel cylinders of different but uniform conductivities (1, 2, 3 or 5 s/m). The diameter of each cylinder was 3.5 cm and length was 4 cm. The 4 cylinders were placed inside a bigger cylinder of uniform conductivity (4 s/m). The whole phantom had uniform relative permeability of 1 and relative permittivity 100. The phantom was situated in a uniform magnetic field of 3 T. A transient magnetic field representing the MRI ramp gradient was applied. The gradient was the same in all three axes and the amplitude was 0.04 T/m. The duration of the pulse was 15 ms with a slew rate of 200 T/m/s. A gel phantom made of carrageenan and agarose was prepared. The phantom had identical dimensions and material properties as the simulation. In particular, T1, T2 and magnetic susceptibility parameters were kept the same throughout the phantom to eliminate confounding effects of differential relaxation and susceptibility. Two small empty plastic tubes were placed next to one cylinder (3 s/m) as fiducially markers. Gradient echo images were acquired on a 3T GE MR750 scanner using the sequence shown in Fig. 1. A healthy adult volunteer was imaged with the same sequence but slightly different parameters.

RESULTS: Finite element simulation revealed visible perturbation of electromagnetic fields induced by the switching of gradients within the phantom. Fig. 2 shows the EM field distribution at t = 163 µs after the gradient is switched off. As can been seen, the electrical fields within the four cylinders are distinctively different. Most prominent magnetic field was observed at the boundaries between different conductivities. This is different from the electrical field where a relatively more homogeneous field was observed within each cylinder. Fig. 3 shows the phase images of the physical phantom with gradient polarity of [1 1 1] and with polarity of [-1 -1 -1]. Phase differences between the two polarities revealed clear contrast between different conductivities. Similar to the simulation, the boundaries between the cylinders generally have larger phase offset. Fig. 4 shows the phase images (difference between opposing gradients) induced by eddy currents. Clear tissue contrast is present throughout the brain among CSF, gray and white matter.

DISCUSSIONS AND CONCLUSIONS: In this study, theoretical relationships between the conductivity tensor and eddy currents were derived based on Maxwell's equations. The two quantities were related by the electromagnetic field induced by the time varying eddy currents. The electric conductivity was treated generally as anisotropic and described by a symmetric rank-2 tensor. Although the electric conductivity at high frequency was believed to be relatively isotropic, the "DC" (or very low-frequency) conductivity is anisotropic. From the phase maps measured by MRI, conductivity tensor can be calculated by solving a set of partial differential equations. We demonstrated, using simulation, phantom and in vivo brain experiments, that effects induced by eddy currents is measurable with standard MRI equipments. To measure the conductivity tensor, two experimental steps are involved: 1) applying pulsed gradients in multiple orientations and 2) measuring the
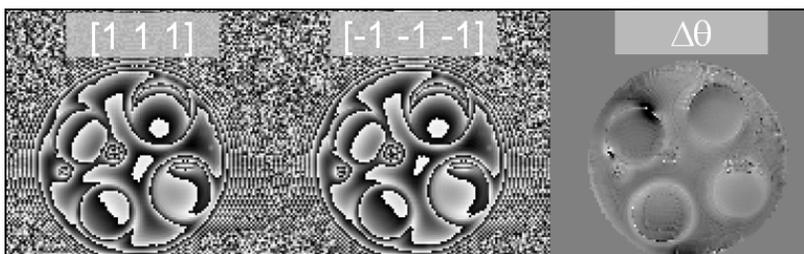

Fig. 3. Measured phase with opposing gradients (2 left images) and phase due to eddy currents (right) as computed as the difference between the phase maps.
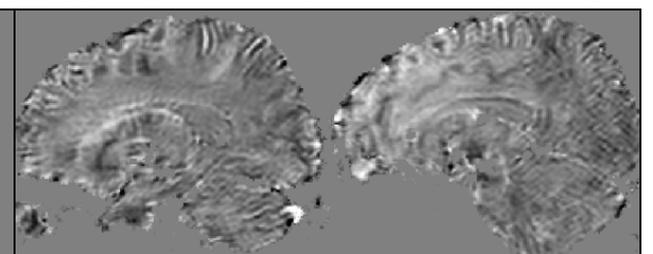

Fig. 4. Phase maps induced by eddy current in two slices of a human brain measured in vivo at 3T.

magnetic field induced by eddy currents. In conclusion, the relationships between conductivity tensor and eddy current were derived. A method was proposed and demonstrated to measure the conductivity using pulsed field gradients. The proposed technique allows the mapping of electric conductivity and conductivity tensor in vivo and non-invasively with MRI.

REFERENCES: 1 Scott GC et al, IEEE Trans Med Imaging 1991; 10(3):362-374. 2. Sersa I et al, Magn Reson Med 1997; 37(3):404-409. 3. Oh SH et al, Magn Reson Med 2003; 50(4):875-878. 4. Katscher U et al, IEEE Trans Med Imaging 2009; 28(9):1365-1374. 5. van Lier AL, et al, Magn Reson Med 2012; 67(2):552-561. 6. Haacke EM et al, Phys Med Biol 1991; 36(6):723-734.