Measuring electrical conductivity at low frequency using the eddy currents induced by the imaging gradients.

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Introduction: The complex permittivity (ε^*) of biological tissues depends on their biochemical composition and the applied frequency. Best known is the effect of cell membranes (Maxwell-Wagner effect) leading to a frequency dependent tissue conductivity (β-dispersion band at about 1MHz) [1]. Various techniques have been developed to measure tissue conductivity in Hz-MHz range. In MR current density imaging (MR-CDI) [2,3] and MR electrical impedance mapping (MR-EIT) [4], an external current is injected into the tissue inducing local changes in the B_0 (Bz) field. This allows for the determination of current density and conductivity using MR phase mapping. In contrast, electrical properties tomography (RF-EPT) [5,6] determines tissue conductivity by measuring local B1+ distortions without external current source. This method, however, is fixed to the Larmor frequency, which is far above the β-dispersion band. In this study we investigate a related method that measures the tissue conductivity in the biologically interesting low frequency (LF,=Hz-kHz) range [8]. A first implementation of this method – LF-EPT– is based on similar reconstruction principles as MR-CDI, but it employs the imaging gradient instead of electrodes to induce (eddy) currents.

Theory: The reconstruction is based on Ampere's circuital law which relates the curl of the magnetic field to the total current density. In the kHz frequency range, the contribution related to the displacement current (Maxwell's correction) can be omitted for biological tissue. Thus, only the free current density related to the tissue conductivity remains (Fig 1). The frequency band of the induced current depends on ramping process (signal shape) of the gradient. By varying this shape several low frequency ranges can be probed.

$$\nabla \times B \approx J = \mu\sigma E \quad [1]$$

$$\text{if } \mu\sigma >> \mu\varepsilon\omega \quad [2]$$

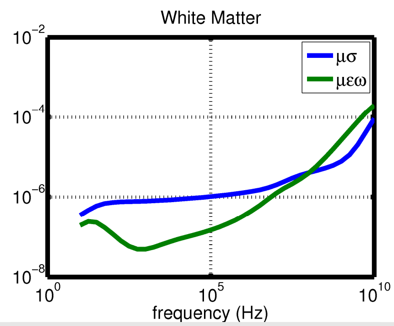

Fig 1: Frequency dependence of dielectric properties of white matter. In the kHz range the requirement in Eq. 2 is true.

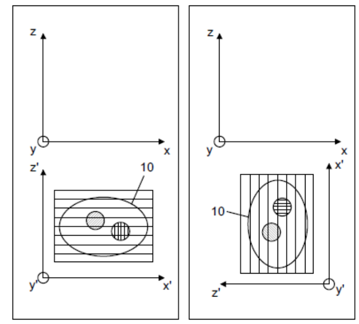

Fig. 2: The phantom is measured in two orientation to compute J_z through a curl operation (see Eq. 1).

Material and Methods: The measurement method is essentially equal to the measurement procedure for RF-EPT. Two different phase images are acquired with a spin echo sequence (TR = 1200ms, TE = 5.3 ms, resolution 1×1×3 mm³) using two opposing read out directions [6]. Measurements were done on a 3T MR system (Achieva, Philips Healthcare, Best, the Netherlands). Two phantoms were investigated, one with 3 different cylindrical saline compartments (each 200 cm³, conductivities 0.0/2.0/0.8 S/m), the other with 2 compartments of saline and uncooked apple sauce (each 200 cm³, conductivities 0.8/0.2 S/m at 128MHz) In the RF-EPT, the contribution of eddy currents was eliminated by adding the two phase images. In LF-EPT, the contribution of the RF magnetic field was eliminated by subtracting the phase images, resulting in twice the eddy current induced phase. This phase was converted to B_z by including the echo time and gyromagnetic ratio. To obtain the induced current distribution from the B_z field, we employed a reconstruction method based on [2]. This method requires 2 orientations of the phantom to compute one component of the curl of B1 (Eq. 1) resulting in the current density component $J_z = \partial_y H_x - \partial_x H_y$ (Fig. 2).

Results and Discussion: In Figure 3, the results are shown for the two phantoms. The RF conductivity using RF-EPT shows clearly the expected conductivity contrast (Fig. 3b). The J_z current density from LF-EPT shows a contrast consistent with the differences in saline concentrations. These findings correspond with the shapes of the central phase profiles, i.e. the parabolic curvature for the RF case and the linear slope of the LF case (Fig. 3a). Also, comparing saline and apple sauce (Fig 3c), the RF phase profiles exhibit the expected parabolic curvatures. Their LF phase profiles are, however, almost identical suggesting that the induced current densities are equal at LF. This could suggest different frequency dependences of the conductivity for water and apple sauce. However, as the current density is a mixed quantity consisting of conductivity and electric field, that cannot be confirmed yet. Future research is needed to reconstruct LF conductivity from current density maps, and also avoiding the need for measurements of two orientations [8].

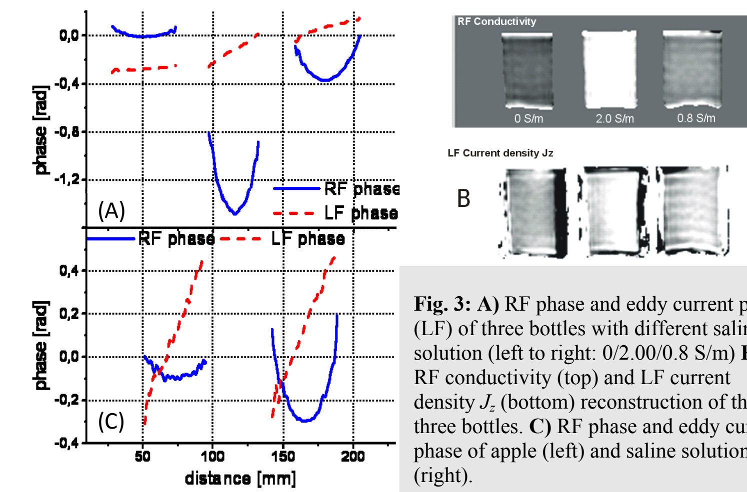

Fig. 3: A) RF phase and eddy current phase (LF) of three bottles with different saline solution (left to right: 0/2.00/0.8 S/m) **B)** RF conductivity (top) and LF current density J_z (bottom) reconstruction of the three bottles. **C)** RF phase and eddy current phase of apple (left) and saline solution (right).

Conclusions: We investigated a method to derive information about LF induced current, which is related to the conductivity of biological material, using induced eddy currents generated by the imaging gradients. First experiments show that this method is feasible in phantoms. Information about LF conductivity is interesting as it is directly related to cellular structures.

References:**1.** Martinsen et al., Encyclopedia of Surface and Colloid Science, 2643-52, 2002 **2.** Scott et *al*., IEEE Trans. Med. Imag. 10:362-74, *1991* **3.** Joy et *al*., 31st Annual International Conference of the IEEE EMBS, p.3158-61, **4.** Woo et *al*., Proc. SPIE 2299:377–85, 1994 **5.**Katscher et *al*., IEEE Trans. Med. Imag. 28:1365-74, *2009* **6.**van Lier et *al.,* Mag Res Med, DOI:10.1002/mrm.22995 **7.**De Geeter, Conf Proc IEEE Eng Med Biol Soc.;2010:5669-72., 2010 **8.**Jeon et *al.,* J. Biomed. Eng. Res. 30 279–87, 2009