New method to quantify RF induced currents inside conductive wires

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Background and purpose Various studies reported significant local tissue heating at tips of electrically conductive wires as guidewires in MR guided interventions *[1,2]*. This heating is caused by the radiofrequency (RF) electromagnetic field needed to generate an MR image. When this field is applied on a conductive wire its free charge carriers are instantly reorganized to keep the electric field normal to its surface. The moving charge carriers induce a current inside the wire producing a tangential magnetic field. Furthermore the charge carriers build up at the wire ends resulting in a higher local electric field that causes the above mentioned tissue heating. This heating becomes a hazard for patient safety when the RF waves can resonate along the conductive wire for certain wire lengths increasing this electric field intensity. Since it is hard to state the wire length at which resonance occurs *[1]*, there is a need for a tool to monitor the tissue heating at the tip of a conductive wire. In this study we investigated the possibility to estimate the induced current from the B_1^+ distortion around the wire.

Material and methods A copper wire (L=20 cm, d=1.7 mm) was inserted to different depths into a plastic tube (L=20 cm, d=12.5 cm) filled with gelatine, including an insertion depth where no resonance occurs and an insertion depth at which RF waves resonate. The phantom was placed inside a SENSE-Tx/Rx head coil of 3T MR scanner. The wire was located along the longitudinal axis of the scanner. For each insertion depth several spoiled Gradient Echo (GE) images were acquired using several nominal flip angles (TR/TE=300 ms/1.54 ms, FOV=120/120/209 mm^3, Acq voxel=1.0/1.0/1.0 mm^3, NSA=3, flip angles (θ_{nom}) 2,4,6,10,25,50,80,110,150^o). To deal with the high dynamic range of the B_1^+ distortion around the wire, the signal equation for spoiled GE sequence was fit for different flip angle combinations (see equation 1). Datasets combinations with high θ_{nom} are sensitive to low λ_{trans} and vice versa. In this way an optimal λ_{trans} map was generated.

$$SI(\bar{r}) \propto C \cdot \frac{\sin(\lambda_{trans}(\bar{r})\cdot\theta_{nom})\cdot\left(1-e^{-TR/T1}\right)}{1-e^{-TR/T1}\cdot\cos(\lambda_{trans}(\bar{r})\cdot\theta_{nom})}$$

where the fit output parameters are: λ_{trans} = transmit sensitivity and C = constant (eq 1)

The transmit sensitivity map was converted to a B_1^+ map by calculating an equivalent B_1^+ amplitude for a rectangular pulse resulting in an identical average flip angle over the slice profile. The B_1^+ map was assumed to be a summation of a constant quadrature B_1^+ (B_{quad}) field produced by the normal body coil, and a pure tangential magnetic field (B_φ) produced by the wire. Using standard complex vector summation the following equation was defined for the angular dependence of the B_1^+ distortion around the wire, where: θ = geometric angle, φ_0 = phase offset, r=radius:

$$\left|B_1^+\right| = \sqrt{\left(\left(\frac{B_\varphi}{2}\right)^2 + B_{quad}^2 - B_{quad}B_{phi}\sin(\theta+\varphi_0)\right)} \qquad \text{(eq 2)}$$

By fitting this model to a measured angular B_1^+ profile around the wire, B_{quad} and B_φ can be determined. By converting the B_φ to a H_φ and applying Ampère's law in intergral form along a circular profile, the current through the wire can be determined quantitatively. This process can be repeated for several radial positions, resulting in a plot of the measured current versus the radial position.

Results and discussion Due to current flowing in the wire the B_1^+ map is highly inhomogeneous (see Figure 1). Using the several nominal flip angle combination per B_1^+ map we were able to obtain reliable B_1^+ maps up to 3 mm from the wire. A typical example of a measured angular B_1^+ profile is shown in Figure 2 together with a fit according to equation 2. The goodness of the fit indicates the validity of this fit equation. In Figure 3 an example of the radial dependence of the measured current is shown. The current profile starts out flat, however, for increasing radius the measured current becomes higher. This can be explained by the contribution of the electric field parallel to the wire, which can only be neglected for small radii. The current should therefore be estimated nearby the wire. Figure 4 shows a nice demonstration of the current mapping technique where the current profile is depicted along a copper wire for resonant and non-resonant wire length.

Conclusion We have developed a method to determine quantitatively the induced current in a wire from its B_1^+ distortion. With this methods we are able to quantify the standing wave current pattern on wires for resonant and non-resonant conditions. This creates a powerful instrument to investigate the resonant behaviour of RF waves along metallic wires used for MRI guided interventions. In principle, the methodology is also applicable for in-vivo purposes. The next step is to use these current profile to estimate the electric field intensity at the wire tip and to estimate the tissue heating.

References:
[1] M.K. Konings et al. "Heating around intravascular guidewires by resonating RF waves. JMRI 12:79-85, 2000
[2] M.F. Dempsey et al. "Investigation of the factors responsible for burns during MRI", JMRI 12:627-631, 2001

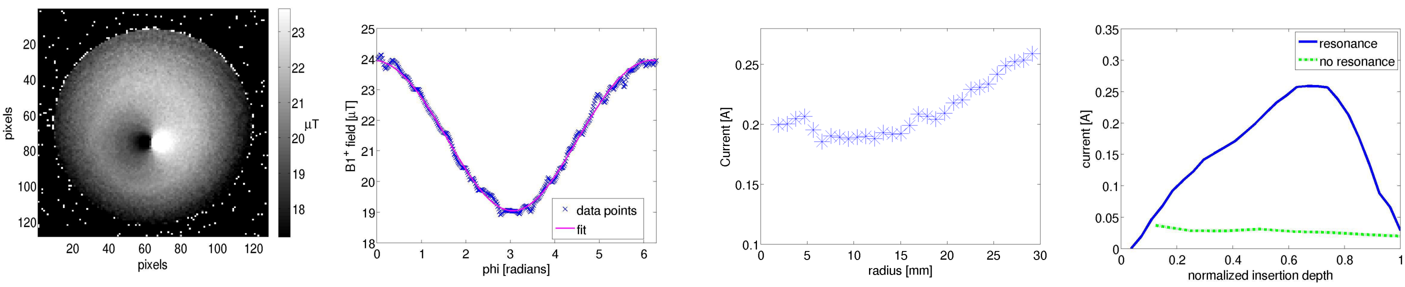

Fig: (1) inhomogeneous B1$^+$ map caused by the presence of a conductive wire, (2) measured B1$^+$ profile together with a fit, (3) radial dependence of the measured current (radius = 9 mm), (4) current profile along wires for resonant and non-resonant conditions.