Using MR magnitude imaging to determine the spatial distribution of the changes of magnetic field induced by sub-µA electric current

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Introduction MRI-based methods for the direct detection of neuronal currents have attracted much more interest recently [1-6]. Much experimental work has been carried out with the express aim of establishing detection thresholds and sensitivity to the flowing currents. However, in some of these experiments, the influence of magnetic susceptibility on detection was not considered. Here, we present a phantom-based measurement to show the influence of susceptibility enhancement on detection sensitivity. The measurements were performed on a 1.5T MR scanner and the results were obtained from MR magnitude images.

Methods The phantom and the electrical circuit used in the measurement are presented in Fig.1. The phantom (diameter/height = 20cm/16cm) was filled with distilled water. Two wires, Cu and air-susceptibility compensated (SC) of diameters 0.3mm and 0.8mm respectively, with different susceptibilities were located 3.5cm from the phantom wall. The two wires in the phantom were vertically positioned and perpendicular to the static magnetic field.

The circuit consisted of three timers (T1, T2, T3), three resistors (R1, R2, R3) and diode D. The two types of wires were connected in series. By changing one of the resistors, we can obtain the nominal currents (I1, I2, I3) in a broad range (95.5, 76.8, 43.0, 11.1, 5.4, 1.1, 0.8, 0.5, 0.2, 0.1 and 0μA) which is indicated in Fig.1. The current flowing through the wires is a combination of three pulsed boxcar waveforms (ON/OFF: 3.5s/3.5s, 6s/6s, 11s/11s), corresponding to three frequencies (1/7s = 143mHz, 1/12s = 83mHz, 1/22s = 45mHz). Current in different combinations of I1, I2 and I3 was used in the experiment. The measurements were repeated several times. The nominal values of the currents were measured with a multimeter (FLUKE-87V, Test Equipment Depot, MA, USA). The boxcar current waveform and durations of the current ON/OFF time were examined using an oscilloscope (Tektronix Inc Beaverton OR USA, TDS 3054, 500MHz, 5Gs/s).
The measurements were carried out on a 1.5T Siemens Sonata scanner. MR magnitude images were acquired using a single-shot, gradient-echo EPI sequence in coronal orientation. Sequence parameters were: TR/TE/FA=200ms/30ms/15°, matrix size = 64x64; FoV=320mmx320mm; slice thickness=5mm; bandwidth = 2442Hz/px. During current flow in the wires, 900 magnitude images were acquired from a single slice. The spatial spectrum distributions of the detected MR magnitude signal were analyzed.

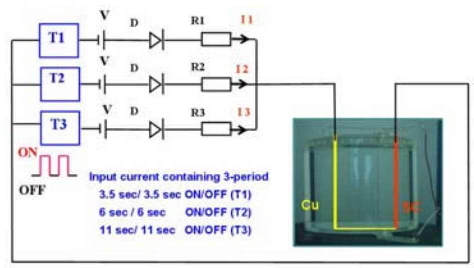

Fig.1 The circuit and the phantom. By changing resistors (R1, R2, R3), we can obtain different nominal currents (I1, I2, I3), V =4.8 Voltage.

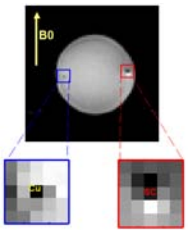

Fig.2 Two 5x5 voxel-matrices outlined around Cu-wire (left) and SC-wire (right). Voxels including wires are marked as 'Cu' and 'SC'.

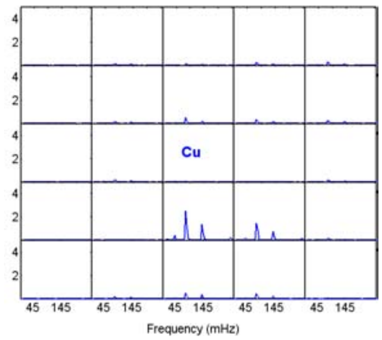

Fig.3 Spatial distribution of MR spectra on the voxel-matrix around the Cu wire for the current (I1/I2/I3=0.1/0.5/0.8µA). The voxel containing the Cu wire is marked 'Cu'.

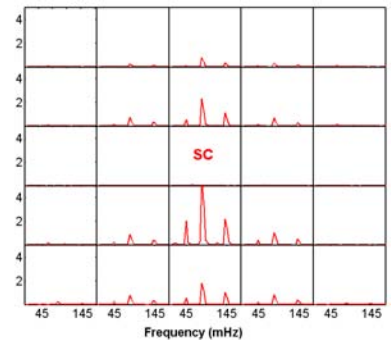

Fig.4 Same as Fig.3 but for the wire 'SC'.

Results and Discussion The spatial distributions of changes of the magnetic field generated by sub-μA electric currents were measured for the voxel-matrix outlined in Fig.2. The susceptibility enhancement effect arising from the two different wires was examined by comparing the distributions of spectra at different voxels. Figs. 3 and 4 show the spatial distributions of the power spectra of the MR signal in the two voxel-matrices around the two wires.

Assuming the wire as a long circular cylinder of radius a, the magnetic field offset induced by susceptibility difference $\Delta\chi$ can be expressed as [7]:

$\Delta B(sus) = \Delta\chi / 2B_0$, (inside the cylinder, independent on cylinder radius) (**1**); $\Delta B(sus) = \Delta\chi / 2B_0 a^2 (z^2 - x^2)/(x^2 + z^2)^2$, (outside the cylinder) (**2**)

(SI units, the cylinder along y-axis and **B**0 along z-axis). The larger the difference $|\Delta\chi| = |\chi_{water} - \chi_{wire}|$, the bigger the magnetic field offset, and the stronger the influence of the susceptibility enhancement on the detection threshold and sensitivity. Take Cu wire as an example, on the surface of the Cu wire, the susceptibility-induced magnetic field offset in the B0 =1.5T MR scanner can be calculated as $\Delta B(sus, \text{on the surface of wire}) = (1/2)\Delta\chi B_0 \approx 4.35\times10^{-7}T$ by inserting $\chi(\text{Cu}) = -9.63\times10^{-6}$ and $\chi(water) = -9.05\times10^{-6}$ (for 37°C) [7] into eq.(1). From eq.(2), for a voxel at the location 10mm away from the wire (x = 0 and z =10mm, the Cu-wire a = 0.15mm), the magnetic field offset induced from the susceptibility can be estimated as $\Delta B(sus) \approx 4.35\times10^{-7}T \times (0.15\times10^{-3})^2 / (10\times10^{-3})^2 = 9.79\times10^{-11}T$. Electric current ($I$ = 0.1μA) generated magnetic field at a voxel of 10mm away from the Cu-wire is $\Delta B(current) = 2\mu_0 I / r = 2\times(4\pi\times10^{-7})\times(1\times10^{-7})/(10\times10^{-3})T = 2.51\times10^{-11}T$, which is smaller than that of susceptibility enhancement. Due to $\chi(\text{SC}) = \chi(air) = 0$, $|\Delta\chi'| = |\chi(SC) - \chi(water)| = 9.05\times10^{-6}$ and $|\Delta\chi| = |\chi(Cu) - \chi(water)| = 0.58\times10^{-6}$, then $|\Delta\chi'| > |\Delta\chi|$. Inequality of susceptibility enhancement causes the different detection sensitivity for the same current, which can be seen from Figs. (3) and (4).

The present measurements indicate the following: (1) MR signal enhancement arising from the magnetic susceptibility effect cannot be ignored in determining the detection sensitivity thresholds; (2) No signal can be detected in the voxel containing wire if the wire is located at the centre of the voxel; (3) The detection threshold and sensitivity are affected by the susceptibility of the wire; (4) sub-μA electric current in a wire-phantom is detectable on a 1.5T MR scanner by utilizing the susceptibility enhancement.

References: [1] Bandettini PA et al. Appl. Magn. Reson. **29**(2005)65. [2] Chu R, et al, Neuroimaging, **23**(2004)1059. [3] Xiong J, et al, HBM **20** (2003) 41.
[4] Bodurka J, et al, J. JMR **137** (1999) 265. [5] Bodurka J et al, MRM **47** (2002)1052. [6] Konn D et al, MRM **50** (2003) 40.
[7] Schenck JF, Med Phys **23**(1996) 816-50 (Table V and equations in p.835).