Design of Sample-Immersed Microcoil (SIM) Probes and their Magnetic Field Monitoring Capabilities

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Target audience: This work is relevant to those interested in MRI magnetic field monitoring.

Introduction: Magnetic Field Monitoring (MFM) by transmit/receive (T/R) NMR probes seems to be a promising strategy to measure the static and dynamic B_0 fields involved in MRI[1-2]. In H^1 based probes, further miniaturization of the coils is essential to achieve higher resolution (<500 μm) imaging, but it compromises the signal-to-noise ratio (SNR) and the manufacturing process. Furthermore, eddy currents existing on the copper shield layers used for the probe's RF shielding had exhibited undesired reconstruction artifacts[1]. In this work, we present a sample-immersed microcoil (SIM) probe which offers an optimized SNR approach since no intermediate materials exist between the sample and the microcoil while eddy current effects are expected to be eliminated by using high-impedance RF shielding.

Materials and Methods: 1) *Probe design*. A solenoid (3 turns, 0.3 mm inner diameter (ID)) made out of a thin (0.1 mm) enameled copper wire that functions as a T/R microcoil is attached to a 20 mm long thicker (1 mm) enameled copper wire, connected to a tuning and matching (T/M) circuit board (fiberglass-epoxy, FR4) with resonance frequency of 128 MHz (50 Ω). In order to eliminate the geometrical constraints given by the sample container (i.e. the capillary wall in typical NMR probe designs) we placed the microcoil inside a single ended glass capillary tube (ID=0.4 mm, wall=0.1 mm) previously filled with a solution made of distilled water and $Cu(II)SO_4.5H_2O$ (3.3 g/L) used as sample material in this study, having T_1 and T_2 values of ~100 ms. We surrounded the sample container and copper wires with D_2O for proper susceptibility matching, since its magnetic susceptibility (-9.01 ppm) is close to that of the copper wire (-9.1 ppm) and the water (-9.03 ppm)[3]. We contained the matching material (D_2O) and the circuitry within a cylindrical glass capillary jacket (ID=10 mm). The open end of the sample container was sealed with a drop of hydrophobic epoxy resin susceptibility matched with 0.27 mg of $Dy(III)NO_3.5H_2O$ per gram of epoxy[4]. We also use it to seal the capillary jacket in both ends. The design of the SIM probe keeps a cylindrical shape within its structure to make a homogeneous field distribution inside the probe. The whole schematic design is illustrated in Fig. 1(a). To protect the probe from external RF fields, the capillary jacket was covered by layers of thin electro-magnetic (EM) fabrics, typically used in imaging coils designs. Since they contain pieces of very thin copper wires intertwined with non-conductive non-magnetic materials, its structure is robust for RF shielding without generating eddy currents, suggesting to be a better alternative to the copper layers used in previous designs[1]. Fine retuning and matching was done after all. A non-magnetic coaxial cable connects the T/M circuit with a T/R switching board, which connects to a low-noise signal amplifier and one of the input channels of the spectrometer of a 3T MRI scanner.

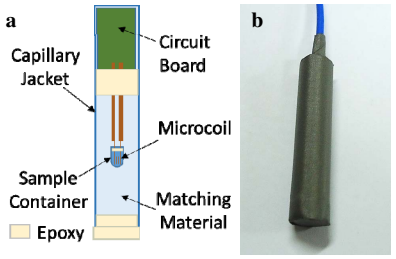

Fig. 1. (a) Schematic of the sample-immersed microcoil (SIM) probe and (b) the physical probe.

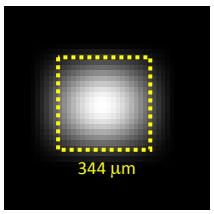

Fig. 2. Gradient-echo image (pixel size: 172 x 172 μm) in sagittal view showing the effective droplet formation of the SIM probe.

2) *Performance Measurements*. After manufacturing, we evaluated the probe's resolution and sensitivity, as well as the field homogeneity inside the probe and its RF shielding efficiency. The SIM probe was placed at the isocenter of the MRI scanner and driven by an RF amplifier (18 kWp) connected to a -40 dB power attenuator and a power splitter delivering around 1 W to the probe, enough power to produce 90° flip angles. We tested the probe's Free-Induction Decay (FID) signal by exciting the sample by a 0.5 ms hard pulse at 0.46 W, acquiring the signal during 0.2 s at an acquisition bandwidth (BW) of 100 kHz. The initial sensitivity of the probe was measured by $\xi = SNR\sqrt{BW}$ [3]. By placing the probe at the magnet isocenter, we observed its droplet formation and sensitivity area by using a gradient-echo sequence (FOV: 11 mm, THK: 5 mm, Points: 64x64, dwell time: 200 μs, TE: 48 ms, TR: 500 ms) in a sagittal view. In order to evaluate the RF shielding efficiency of the probe, we performed a S21 measurement in a bench test using a network analyzer by connecting the SIM probe in one channel and, in the other channel, a head birdcage coil loaded with a homogeneous cylindrical phantom.

Results: A photograph of the manufactured SIM probe including the T/M circuit is presented in Fig. 1(b). Figure 2 shows the droplet formation of the SIM probe obtained by the gradient-echo sequence. The probe is laying horizontally along the z-axis while a read out gradient is applied parallel to the microcoil axes. Since the signal attenuation is equivalent in both spatial directions, we could monitor imaging sequences with resolutions below 200 μm[1]. The first 100 ms of the acquired complex FID signal is shown in Fig. 3. From Fig. 3(a) we can observe that the initial signal strength is reduced to 25% at 100 ms which is what we may expect since the T_2 value of the sample is around this value, supporting a satisfactory field homogeneity inside the probe. We measured the initial sensitivity of the probe by taking the initial value of the measured FID signal divided by the standard deviation of an acquired signal without excitation resulting in an SNR of 180. At a BW of 100 kHz this give us an initial sensitivity of $5.7x10^4$ $Hz^{1/2}$ which is an acceptable value considering the size of the coil and the achieved resolution. The computed time course of the FID's phase is shown in Fig. 3(b). Since the FID was acquired without applying any gradient, a perfectly linear evolution is expected. Therefore, a linear fitting and the difference with the measured phase after unwrapping is also shown as a FID quality metric. The maximum value of the residuals, after applying a five-point moving average filter, is 0.12 rad. RF shielding measurements showed a S21 value of -23 dB when an unshielded SIM probe was placed at the middle of the birdcage coil. After that, the same probe was covered by EM fabrics giving a S21 of -76 dB.

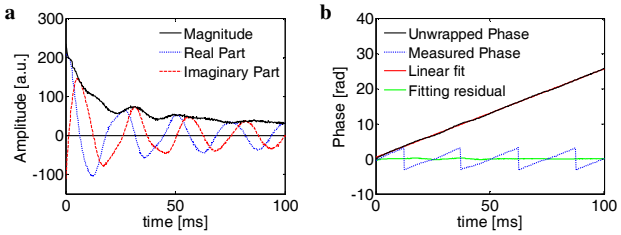

Fig. 3. (a) FID signal of the H^1 sample and (b) the computed phase evolution during a static field measurement compared with an expected linear phase evolution.

Discussions and Conclusions: We introduced a new design of miniaturized H^1-based field sensors offering high resolution without significant SNR losses. By switching the contents of the capillary jacket and the sample container (water and D_2O) the SIM probe can be easily adapted to exploit the advantages of H^2-based NMR probes. With the use of high-impedance RF shielding we can overcome eddy current effects. MFM-assisted reconstructions need to be performed to validate this factor but we believe SIM probes can be an excellent alternative in high resolution MFM applications.

References: [1] Barmet *et al*., Magn Reson Med **62**:269-276, 2009 [2] Sipila, *et al.* Magn Reson Med **65**:1498-1506, 2011 [3] De Zanche *et al*., Magn Reson Med **60**:176-186, 2008 [4] Barmet *et al*., ISMRM **15**:36, 2007