Advances in NMR Probe Technology for Magnetic Field Monitoring

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Introduction

Despite continued advances in MR hardware, imperfections in the magnetic field evolution during MR scans still hamper numerous MR procedures. Field perturbations are caused by a range of mechanisms, including eddy currents, limited gradient bandwidth, and heating effects. Often such errors can be addressed by means of signal processing. However, to do so these errors need to be accurately known. Reproducible field perturbations can be determined approximately by preparatory measurements (1, 2). Alternatively, it has recently been proposed to monitor the relevant field evolution directly during each actual scan, using NMR field probes (3, 4). In this work we present recent advances in the design and use of such probes.

Materials and Methods

The key challenge in designing NMR field probes is obtaining strong and long-lived signals from NMR samples small enough to avoid dephasing by externally applied gradients, i.e. preferably smaller than 1 µl. For extracting strong signals from such a small sample it is essential to mount it tightly in a receiver coil. However, nearby material interfaces tend to induce magnetic field variation in the sample, thus limiting its signal lifetime. This is illustrated in Fig. 1a, showing the fast signal decay of a water droplet in a glass capillary (i.d.=1.4 mm) when surrounded just by air and a tightly wound copper solenoid. A first step in solving this problem is immersing the droplet in a hydrogen-free liquid of similar magnetic susceptibility, e.g. perfluorinated hydrocarbons (Fluorinert, 3M) (5). Besides some residual susceptibility mismatch the downside of this approach is that due to its higher surface tension the water droplet maintains its concave shape, thus exhibiting a bad ratio of volume (i.e. signal) to diameter (i.e. vulnerability to field gradients). This problem has been solved by replacing the water with cyclohexane (C_6H_{12}), immersed in heavy water (D_2O). Cyclohexane combines high proton density with a singlet spectrum, low gas solubility and low surface tension. A polar matching liquid such as D_2O has the additional advantage of permitting perfect titration of the cyclohexane susceptibility (-7.86 ppm) by dissolving a paramagnetic salt, such as copper sulfate (Fig. 1c). However, to fully benefit from this measure the remaining susceptibility variations must be addressed as well. The glass capillary causes no field inhomogeneity in its interior due to its cylindrical shape. However, the copper coil has major detrimental effects, as seen in Fig. 1b,c. The susceptibility of copper (-9.65 ppm) could again be matched approximately by Fluorinert (3,5). However, the match is even less accurate than with water and liquid matching is also not preferred in terms of handling and durability. Therefore an exactly matching solid material has been created by doping a common two-component epoxy system with iron chloride. When cast into the doped epoxy, the coil no longer impairs the field homogeneity, securing the desired signal lifetimes on the order of 100 msec (Fig. 1d). Using exact matching it has been possible to further miniaturize the probe sample to 0.5 µl, contained in a 0.8 mm capillary (Fig. 1e).

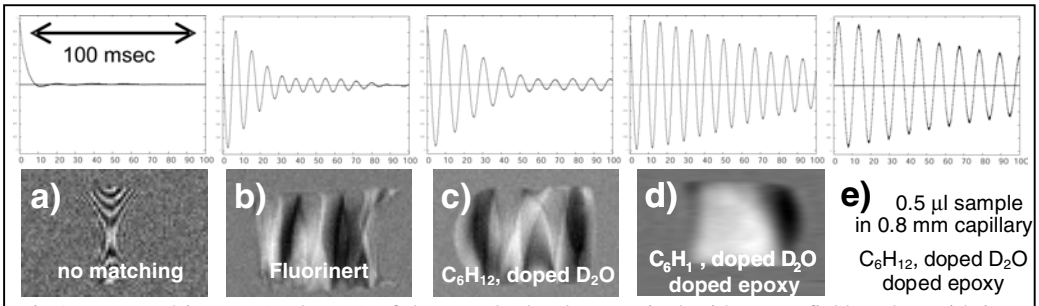

Fig.1 FIDs and images (real parts) of the sample droplet, acquired with NMR field probes with improving magnetic matching. With all matching measures taken, the signal lifetime reaches 100 ms.

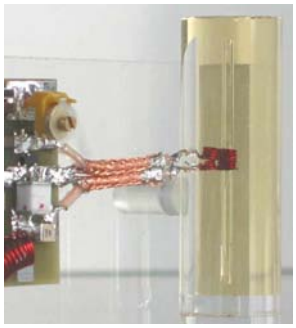

Fig. 2 NMR probe with a 0.5 µl cyclohexane sample in a 0.8 mm Pyrex capillary, cast into paramagnetically doped epoxy.

The final 0.5 µl probe is shown in Fig. 2. The solenoid is connected to a single-stage low-noise FET preamplifier on a 10 cm^2 circuit board that also contains tune/detune circuitry. The complete probe is attached to an acrylic plate for precision mounting. RF crosstalk among field probes as well as between probes and actual imaging coils is minimized by the use of "bazooka" baluns (6). Accurate, fast and repeatable positioning of field probe arrays is enabled by a modular system of acrylic plates with Cartesian grids of mounting holes. The exact geometric probe configuration may thus be readily measured, establishing reliable coordinates independent of the gradient system.

Results and Discussion

Mounted in this fashion, an array of 16 field probes was connected to a 3T whole-body imager (Achieva, Philips Medical Systems, NL) and used to monitor the field evolution during single-shot spiral scanning. Based on the 16 individual probe signals the spatiotemporal phase evolution was determined to second order in a spherical harmonic basis (Fig. 3). The zeroth order (blue) represents the homogeneous (or B_0) phase component, the first order (red) are the familiar k-space coordinates, and the second order (black) represents small mixed and quadratic terms, which arise predominantly from higher-order eddy currents, slight gradient non-linearity, and concomitant gradient field components. Revealing these effects with high accuracy and concurrently with actual scanning, the monitoring approach promises vital input to advanced image reconstruction and applications in MR hardware development and analysis.

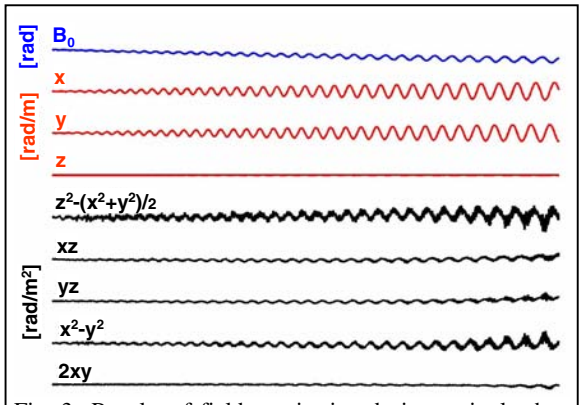

Fig. 3 Results of field monitoring during a single-shot spiral readout. The signals of 16 NMR probes yielded a second-order spherical harmonic expansion of the spatiotemporal phase evolution. The first order terms (red) are the familiar k-space coordinates. (not to scale).

References

(**1**) SB Reeder et al. Magn Reson Med 1997;38:429-439. (**2**) JH Duyn et al. J Magn Reson 1998;132(1): 150-153. (**3**) De Zanche et al. ISMRM 2005 p. 791. (**4**) Pruessmann et al. ISMRM 2005 p. 681. (**5**) DL Olson et al. Science 270, No. 5244, p1967 (1995). (**6**) JD Kraus. Antennas, 3rd edition (2002), p. 804.