Towards routine field monitoring for MRI: a transmit/receive system based on shielded NMR probes

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Introduction: Magnetic field monitoring with NMR probes has recently been introduced for addressing dynamic field perturbations and gradient imperfections in MR systems (1). The monitoring approach has been demonstrated to be sufficiently sensitive to reveal the relevant field evolution in MRI, in particular the dynamics of gradient fields, with temporal resolutions in the range of hundreds of kHz, corresponding to typical MRI acquisition frequencies. However, one major obstacle to broader application has been the use of probes designed for receive-only operation, requiring external RF excitation of NMR in the probe droplet, e.g. by the body coil. Such probes are difficult to operate independently from the actual MR experiment to be monitored. RF pulses used for exciting the NMR probes will generally interfere with the imaging sequence and vice versa. A promising way of overcoming this problem is the transition to transmit/receive (T/R) probes with a separate RF transmit chain. Such probes can be excited independently at any time during an experiment without disturbing it. Autonomous RF excitation also offers the important option of shielding the probes against MR signal contamination from the nearby imaging object. Such protection against confounding object signals will help greatly towards routine field monitoring with freely positionable probes.
In the present work we report the implementation of these advances, including the design of shielded T/R monitoring probes as well as suitable transmit and receive hardware and basic operating principles.

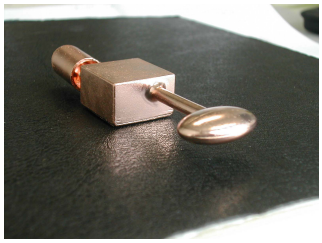

Fig. 1: Shielded probehead with tuning and matching circuit.

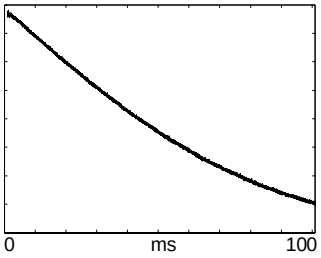

Fig. 2 Probe FID over 100ms.

Methods: The basic requirements for the probeheads are that they must yield NMR signals of very high SNR, even at short repetition times, and of long lifetime for monitoring long gradient sequences. To ensure long signal lifetime in the presence of strong gradient fields the probe droplets must be very small. For the present implementation $CuSO_4$-doped water samples were placed in borosilicate capillaries of 0.8 mm in diameter. For signal excitation and reception they were placed in 4-turn solenoids made from 0.1 mm copper wire, resulting in a sensitive volume that extends roughly 0.8 mm also along the capillary axis. The capillaries were cast into an epoxy casing for easy handling and durability. To avoid susceptibility broadening of the probe signal the epoxy resin was chosen such as to match the magnetic susceptibility of the solenoid (2,3) and the casing was given the shape of an ellipsoid, preserving the homogeneity of the external field on its inside. For RF shielding the casing was electro-plated with 22 microns of copper, i.e. roughly four times the RF skin depth in copper at 128 MHz. The copper shield also encompasses a tuning and matching circuit enclosed in a small box that is separated by a few cm from the probehead, again to avoid susceptibility effects. A fully assembled probehead in shown in Fig.1.
For probe excitation a basic transmit RF chain was assembled from a pulse generator, a modulated frequency generator and a 300W RF amplifier. The amplifier output is split eight ways using a cascade of 7 quadrature hybrids for a maximum of eight monitoring probes. An individual attenuator on each output permits per-probe flip angle adjustment. For signal reception the probes are connected to regular receive channels of a 3T Philips Achieva spectrometer. Switching between transmit and receive operation is performed by a PIN diode T/R switch, which also includes two-stage MOSFET preamplification (net gain = 45 dB) for probe signals.
Due to their small size and RF losses the NMR probes can be excited with little RF power (in the range of 10W in total), enabling large bandwidth pulses with durations of only several µs. This is important to allow for potentially large excursions in probe Larmor frequency due to strong gradients in the imaging sequence. For controlling the probe excitation the scanning software of the 3T system was suitably extended to provide TTL triggers at suitable times during a monitored imaging sequence, e.g., right after the regular excitation pulse in any gradient-echo sequence.

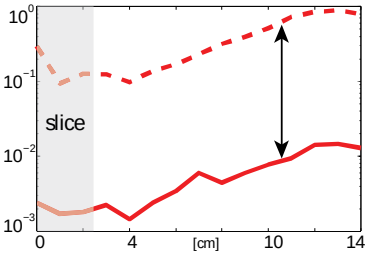

Fig. 3 Probe contamination by MR signal from a bottle, relative to strength of probe signal. Solid line: shielded probe, dashed line: unshielded probe.

Results: A first validation step concerned the SNR yield of the newly designed probeheads and receive electronics. It was assessed as approximately $10^5\,Hz^{1/2}$ for 90 degree probe excitation, indicating that at an upper bound of 1 MHz for the acquisition bandwidth the SNR will still be 100, which is amply sufficient for following the relevant field evolution (3). Figure 2 shows the magnitude time course of a typical probe FID, recorded with a bandwidth of 100 kHz. The second critical aspect is the effectiveness of the copper shield in suppressing contamination by MR signal from the imaging target. It was assessed by placing one shielded and one unshielded probe next to a large water phantom and studying FID signals from the probes after exciting a thick slice (50 mm) of the phantom at varying distance from the probes. The results of this test are shown in Fig. 3, illustrating that the copper shield reduces contamination by MR signal from the bottle by a sufficient factor of approximately 100 (40 dB).
One important aspect of the copper shield is that it does not only give rise to RF eddy currents as desired but also slightly shields fields of lower frequency, such as the gradient fields that the probes are there to monitor. To minimize this problem the copper shield was chosen as thin as possible. Nevertheless is still causes a slight delay in field response in the probe droplet. This delay can be readily assessed by receiving FID signals simultaneously from a shielded and an unshielded probe under the influence of short gradient pulses. Using this method the probe delay was assessed to be 6 microseconds for the current probe design with 22 micron copper shielding.
For monitoring imaging experiments four such probes were mounted on a commercial 8-channel head coil array (MRI Devices) in a tetrahedral arrangement, with a water phantom placed inside. An example of monitored gradient-echo imaging is shown in Fig. 4. To obtain this image the effective k-space trajectory was calculated from the phase time courses of the four monitoring signals (1), followed by coil-wise gridding reconstruction along this trajectory and sum-of-squares combination.

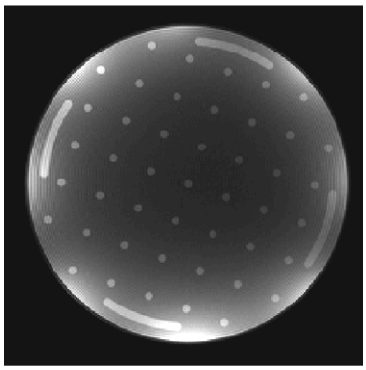

Fig. 4 Gradient-echo image , reconstructed from monitoring data obtained with 4 T/R probes.

Conclusion: Transmit/receive probe operation is crucial step towards the flexibl application of field monitoring for in-vivo MRI. It has been shown that miniaturized NMR probeheads can be readily equipped with T/R capability. Thin copper plating offers sufficient RF shielding, while limiting the effect of gradient eddy currents to a fixed delay similar to those known from gradient coils. Combined with suitable hardware additions and software modifications an array of such probes forms a largely autonomous monitoring system. The probes do still rely on the system spectrometer for signal reception and digitization. This, however, hardly affects the flexibility of the monitoring approach because field monitoring is typically desired during the acquisition of imaging data. Synchronization of the data acquisition with the actual MRI procedure is in fact very convenient when using the probe data for image reconstruction, as has been confirmed by an initial imaging application.

References: (1) Pruessmann et al. ISMRM 2005 p. 681. (2) DL Olson et al. Science 270, No. 5244, p1967 (1995). (3) De Zanche et al. MRM, in press (2007).