NMR probes for magnetic field monitoring during MRI

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Introduction

NMR probes containing small samples of water can be used to measure minute temporal variations in magnetic fields by following the phase of the spin signal after an excitation pulse [1]. Sequence-specific imperfections in gradient performance and eddy currents can result in image artifacts due to the violation of the underlying assumptions of MR imaging, i.e. uniform, constant B_0, and high-fidelity gradient waveforms. Information gathered from a constellation of field monitoring probes can be used during image reconstruction to remove such artifacts, ultimately allowing the use of less stringent specifications on eddy currents and gradient fidelity.

Methods

The realization of such a system must overcome two fundamental problems: a) the acquired signals must not be affected by cross-talk from other samples or from the object that is being imaged, and b) long readouts (~100ms, e.g., to capture a single-shot spiral or echo-planar acquisition) require long probe signal decay times which are limited by local static field inhomogeneities caused by the sample and probe. Furthermore, to avoid dephasing by the imaging gradients the dimensions of the samples must be comparable to, or smaller than the desired image resolution, resulting in volumes of the order of 1μℓ.

High-SNR signal detection was performed inductively by solenoidal microcoils connected to low-noise preamplifiers. Cross-talk was limited primarily by reducing unwanted inductive pickup. All signal paths or inductors (e.g. matching, RF chokes) that could receive NMR signal because of their geometrical arrangement were either shielded or routed to minimize flux linkage with nuclear spins within the imaging volume. The circuit board containing detuning, matching and preamplification was consequently shielded and its connection to the solenoid containing the sample was made using a coaxial cable. Since in this implementation the probes are to be excited by an external field and cannot be shielded, particular attention was required to minimize the sensitivity of this solenoid to spins outside of its interior. The remedy consists of winding a second, parallel solenoid having the same number of turns but opposite orientation (Fig. 1a), thereby minimizing sensitivity to fields outside its immediate vicinity. Further parasitic pickup, as well as cross-talk between channels, is limited by using shielded coaxial cable traps immediately following the preamplifier. Cross-talk between field-measurement channels was found to be negligible under these conditions.

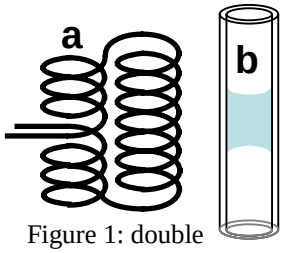

Figure 1: double solenoid (a) and sample capillary (b)

To reduce field inhomogeneities within the sample susceptibility matching techniques were employed [2]. The table below lists the materials used in probe construction and their corresponding magnetic susceptibilities (SI system). Since the largest susceptibility differences occur at the interfaces with air, bubbles in the samples must be avoided by first de-gassing the water. A small droplet of water is then injected inside a precision 2.2mm inner diameter Pyrex capillary (Wilmad, USA) previously filled with a perfluorinated hydrocarbon (FC-77 Fluorinert; 3M, USA) (see Fig. 1b). Fluorinert was also used to displace air within and around the solenoid, enclosing the complete probe within a 2cm diameter cylinder. Due to the residual susceptibility mismatch between FC-77 and copper, the solenoid's diameter was chosen to be 0.5 mm larger than the capillary's 2.5mm outer diameter. Finally, the tuning and preamplifier board was located ~5 cm from the coil to avoid further B_0 inhomogeneities caused by electronic components as well as distortions in transmit B_1 field due to the RF shielding.

material	χ [ppm]	location
air	0.36	surrounding spaces
water	-9.05	sample volume
FC-77	appx. -8	susc.-matching fluid
Pyrex	-11.0	capillary
Cu	-9.65	solenoid

Results

A set of monitoring probes was interfaced to a 1.5T Philips Gyroscan Intera imager. Excitation of the samples was performed using a body transmit coil. An FID signal with, and one without susceptibility matching are shown in Fig. 2. The magnetic field at a probe's position is proportional to the derivative of its signal phase, as shown in Fig. 3 for an example of single-shot spiral acquisition.

Conclusion

The monitoring probes described above are able to measure in great detail the time course of the local magnetic field. Knowledge of gradient infidelities and eddy currents can be derived and incorporated into reconstruction without sequence-specific information. This approach reduces demands on gradient hardware and could prove highly beneficial for EPI and spiral scanning.

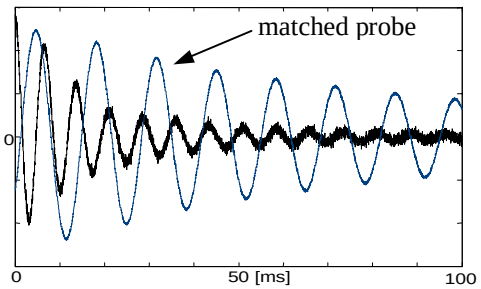

Figure 2: FID signals illustrating longer decay times using the susceptibility matched probe in comparison to the unmatched case.

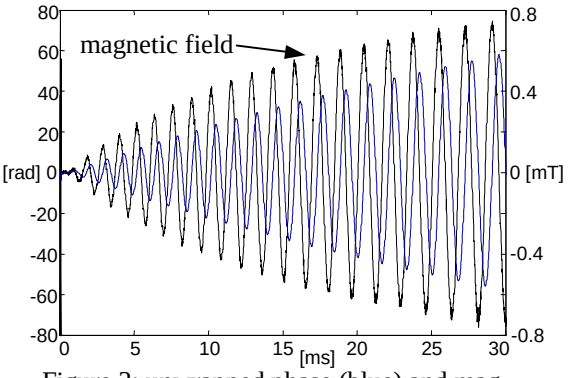

Figure 3: unwrapped phase (blue) and magnetic field (black, obtained by differentiation) during single shot spiral acquisition.

References

1. G Schnur, C Reymond, P Sommer. US Patent 5,731,704 (1998).
2. DL Olson, TL Peck, AG Webb, RL Magin, JV Sweedler. Science, Vol. 270, No. 5244, p1967 (1995).