Continuous 3rd-order field monitoring: Design and application for single-shot shim characterization

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Introduction: Dynamic magnetic field monitoring with NMR probes enables the observation of the spatio-temporal magnetic field evolution during MR experiments [1]. Originally, this approach was limited to finite measurement intervals and k-space excursions since external gradients dephase the probe samples. These limitations were recently overcome by the transition to rapid, interleaved re-excitation of short-lived probe sets, which enable fully continuous field monitoring of arbitrary duration and gradient accrual [2]. So far this approach has been limited to field monitoring up to only first order in space. However, uninterrupted measurement over long times is equally critical in dealing with higher-order fields, particularly in the context of dynamic shimming [3-5], and real-time field control [6]. The need for enhanced measurement capability is exemplified by the task of determining shim impulse response functions (SIRF) [7] for system characterization. So far, SIRF measurements require a large number of partial acquisitions, resulting in long overall measurement duration. In contrast, continuous observation of sufficient sensitivity holds the potential of permitting such characterization in a single shot within seconds, prompting the intriguing perspective of real-time analyses of system properties, e.g., under thermal stress.

The aim of the present work is to accomplish this capability by implementation of 3rd-order fully continuous field monitoring, which poses a range of challenges. Among others, enhanced sensitivity requirements for higher-order field components impose rigorous suppression of parasitic NMR signals from solids in the probeheads. And the substantial increase in probe and channel counts requires advanced considerations for mutual RF decoupling and provisions for massive data flows during continuous measurements.

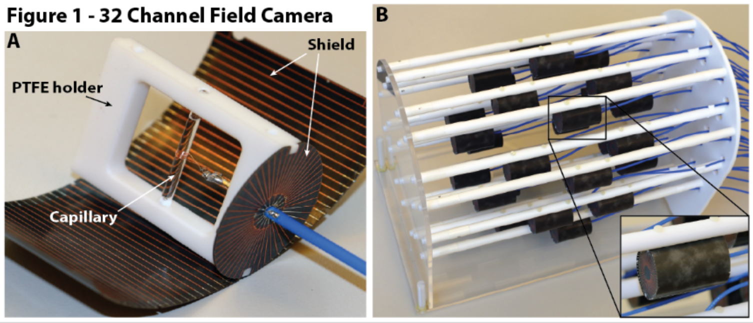

Figure 1 - 32 Channel Field Camera

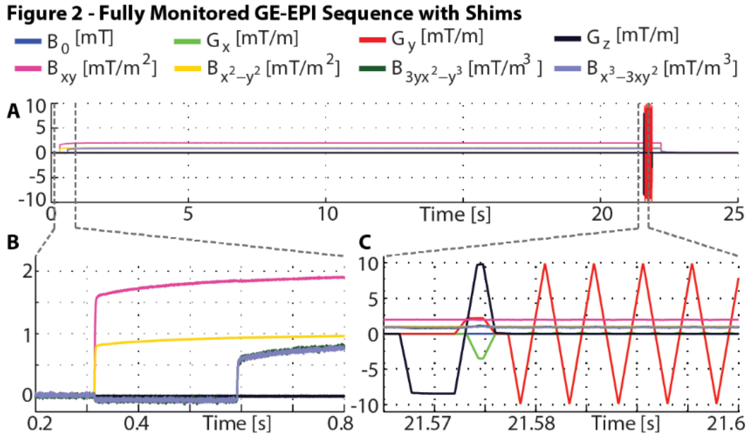

Figure 2 - Fully Monitored GE-EPI Sequence with Shims

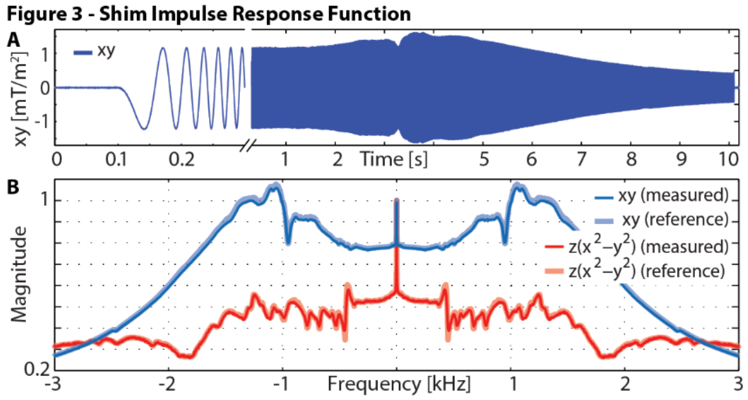

Figure 3 - Shim Impulse Response Function

Methods: A field camera head consisting of 32 ^{1}H field probes, face-centered on a soccer-ball polyhedron, was constructed (Fig. 1.B). Individual probes were built from a 2.2 mm inner diameter glass capillary filled with H_2O and doped with $GdCl_3.6H_2O$ such that $T_2 = 80$ µs. 5 turn solenoids serve as transmit/receive coils. Care was taken to avoid any materials in the vicinity of the coil and electronics which could emit parasitic ^{1}H signals, such as epoxy in printed circuit boards or flux of solder wires. Each probe was further equipped with an RF-shield to reduce coupling between probes due to imperfect balancing and fringe fields (Fig. 1.A). Besides RF suppression the shield was carefully designed not to admit relevant eddy currents in the audio frequency range, resulting in optimized radial and axial conductor patterns. The camera was connected to a custom-built transmit/receive chain and spectrometer laid out for high-SNR signals and real-time signal processing [2]. Continuous field measurement is achieved by rapid re-excitation of these probes with a TR of 180 µs in either a single-set mode or alternating between two sets. The derivatives of the phase evolutions of each multiple-probe readout are transformed into the basis of 3rd-order spherical harmonics and concatenated. The re-excitation-gaps of 15 µs are filled using finite-support interpolation based on knowledge of bandwidth limitation (28 kHz). A single-shot SIRF measurement was performed by continuous 3rd-order monitoring over 10 sec while playing out chirp pulses through a custom shim control unit [7]. Simultaneous self- and cross-term SIRFs were obtained by de-convolution of the measured responses with the input chirp. All measurements were performed in a Philips Achieva 7T system (Philips Healthcare, Cleveland, USA) equipped with a full 3rd-order shim set.

Results/Discussion: Residual coupling between probes in the array was found to be below -78 dB throughout. As a generic monitoring example, Fig. 2.A shows an arbitrary gradient-echo EPI sequence, including the setting of 2nd- and 3rd-order shims during the preparation phases. Fig. 2.B shows a zoomed excerpt of slow shim settling due to eddy currents and Fig. 2.C a detail of slice selection and the EPI readout. Fig. 3.A shows the 10 s time-domain chirp self-response obtained for SIRF measurement of the xy term. Fig. 3.B shows the corresponding SIRF along with that of a selected 3rd-order term (zx^2-zy^2). The slightly brighter and thicker plots in Fig. 3.B represent the corresponding reference data from Ref. [7] and illustrate very good agreement of the novel single-shot and conventional measurements.

Conclusions: The presented system enables fully continuous 3rd-order field monitoring over arbitrary durations with an acquisition duty cycle of 100%, 32 channels, and 1 MHz acquisition bandwidth per channel, limited only by storage space. Its scanner-independent stand-alone nature makes it a versatile tool for system calibration and diagnostics as well as sequence debugging, all of which is expected to increasingly involve dynamic higher-order shim fields. The novel capability of gradient and shim impulse response characterization in just a few seconds is foreseen to enable new ways of MR system monitoring and dynamic calibration, and offer insight into hardware behavior from thermal changes to aging and failure modes.

[1] Barmet C et al. MRM 2008;60(1):187-197, [2] Dietrich BE et al. ISMRM 2011 p. 1842, [3] Blamire AM et al. MRM 1996;36:159-165, [4] Juchem C et al. Concepts Magnetic Res B 2010;37B(3):116-128, [5] Fillmer A et al. ISMRM 2014. p. 864, [6] Duerst Y et al. MRM 2014 doi: 10.1002/mrm.25167, [7] Vannesjo SJ et al. MRM 2013 doi: 10.1002/mrm.24934.