FIELD PROBES FACILITATE HARDWARE DEBUGGING OF LOCAL B_0 COIL ARRAY

USING FIELD PROBES TO DEBUG CUSTOM-BUILT NONLINEAR GRADIENT FOR MRI ACCELERATION

Written by **Rui Tian,** PhD candidate at Max Planck Institute for Biological Cybernetics in Tübingen

An in-house built 8-channel local B_0 coil array is developed to accelerate MRI scans using nonlinear gradient encoding. Field probes serve as a magnetic field oscilloscope, aiding in hardware debugging and ensuring the safety operation of this cutting-edge technology.

To further push MRI speed forward, it is crucial to swiftly capture more physical information within limited acquisition time. This necessitates developing hardware capable of switching the spatial encoding magnetic fields more rapidly. Therefore, we have built an 8-channel local B_0 coil array capable of generating both linear and various nonlinear B_0 fields to explore the optimal magnetic field modulation schemes for image acceleration. By applying independent current waveforms to the local B_0 coil channels during signal readout, we enrich the undersampled k-space data with more informative content, thereby producing high-quality accelerated MRI images after numerical reconstructions.

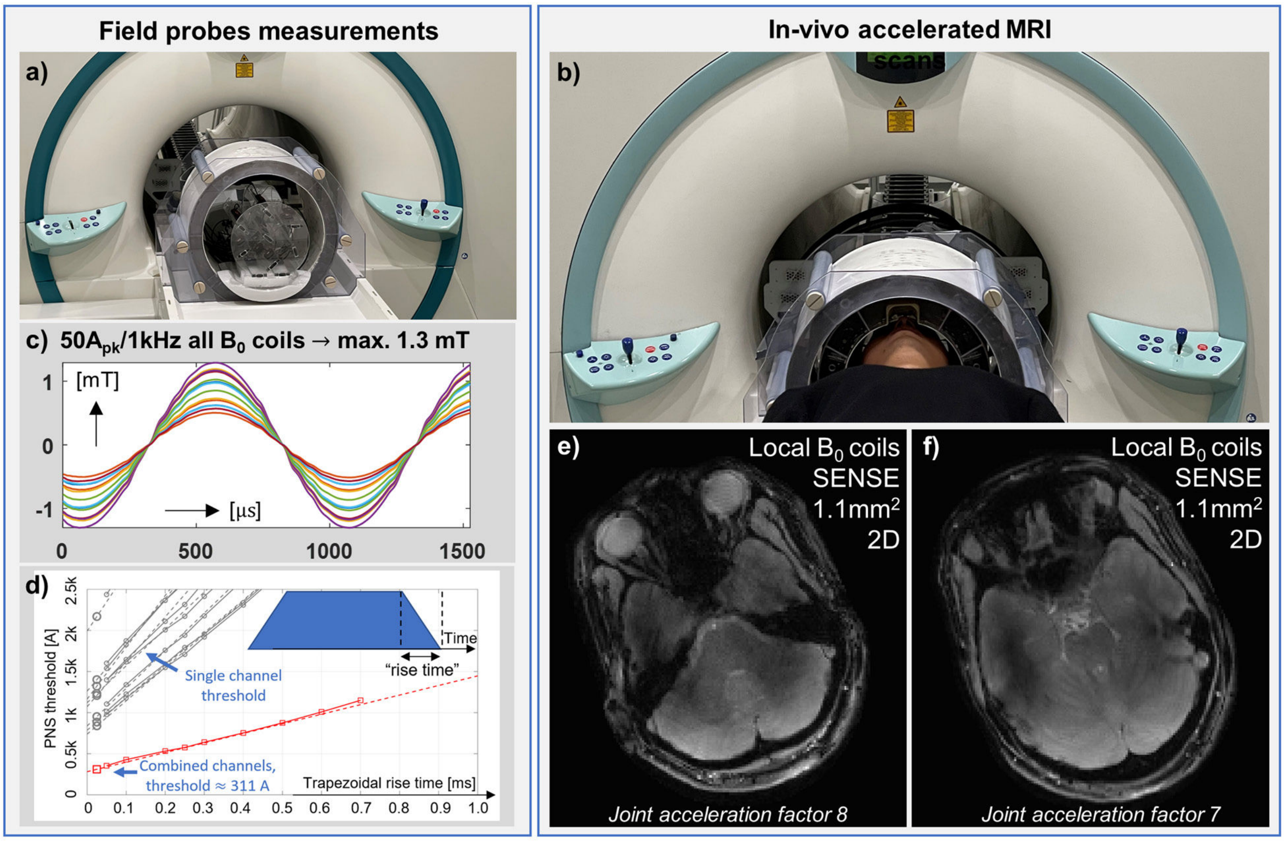


Figure 1: a) The setup of field probes' measurements. b) The setup of in-vivo MRI jointly accelerated by local B_0 coil array and parallel imaging. c) The experimental field probes measurement of the additional oscillating magnetic fields produced by the local B_0 coil array. d) The theoretical PNS thresholds for the local B_0 coils, simulated based on the designed hardware configurations and a realistic human body model. e-f) In-vivo multi-slice 2D FLASH scans jointly accelerated by local B_0 coils modulations and parallel imaging, with least square reconstruction.

USER APPLICATION: **Clip-on Camera**

Field probes serve as a magnetic field oscilloscope to debug and ensure the safety operation of our custom-built hardware. They can examine the additional rapid modulations of B_0 fields separately produced by the local B_0 coils, measuring the oscillating field strength and thus, providing a straightforward and reliable method to experimentally validate the hardware design. This validation confirms the accuracy of the PNS simulation based on the designed hardware configuration, ensuring the safety of human subject in in-vivo scans accelerated by rapid modulations of local B_0 coils.

Results

The field probes measurements confirm the safety of our local B_0 coil array for human subjects, which operates at approximately 6.2 times below the estimated PNS threshold when using a maximum of $50A_{pk}$ sinusoidal currents for B_0 coils modulations. These measurements also allow us to check for modulation waveform distortions, ensuring that the generated oscillating local B_0 fields meet our design expectations, facilitating the hardware debugging.

Consequently, our local B_0 coil array has been successfully applied to in-vivo scans. Assisted by the field probes, the local B_0 coils have been precisely controlled in synchronization of a 9.4T human MRI scanner, to stably produce various spatially varying B_0 fields in oscillations. The sampling efficiency of distinct local B_0 modulation schemes across the entire k-space is quantitatively visualized, using a mathematical framework based on the reproducing Kernel Hilbert space theory (RKHS). The reconstruction has been enhanced by a novel calibration technique to efficiently characterize various additional oscillating local B_0 fields, utilizing current monitors of the power amplifiers and the ESPIRiT algorithm. Thus, we compare several characteristic modulation schemes of local B_0 coils, and select an optimized scheme to achieve approximately 7- to 8-fold joint acceleration factor in conjunction with parallel imaging for 2D multi-slice Cartesian MRI.

Specifically, during the 2D FLASH scans accelerated by local B_0 modulations during signal readout, the linear gradient remains the main "encoder" and leaves a pattern of missing k-space data naturally fit by simply a zig-zag trajectory. Thus, the B_0 modulation field optimized for this sampling scheme turns out to be a linear gradient along the only one undersampled phase encoding dimension, similar to bunched phase encoding but using local gradient hardware. However, this doesn't eliminate potential advantages in signal encoding with more arbitrary magnetic field modulations, particularly considering scenario beyond 2D Cartesian sampling, such as 3D Cartesian and spiral. Meanwhile, the field probes remain essential tools to debug this hardware aiming to produce more sophisticated magnetic field modulations in spatial-temporal domains and further accelerate the MRI scans.

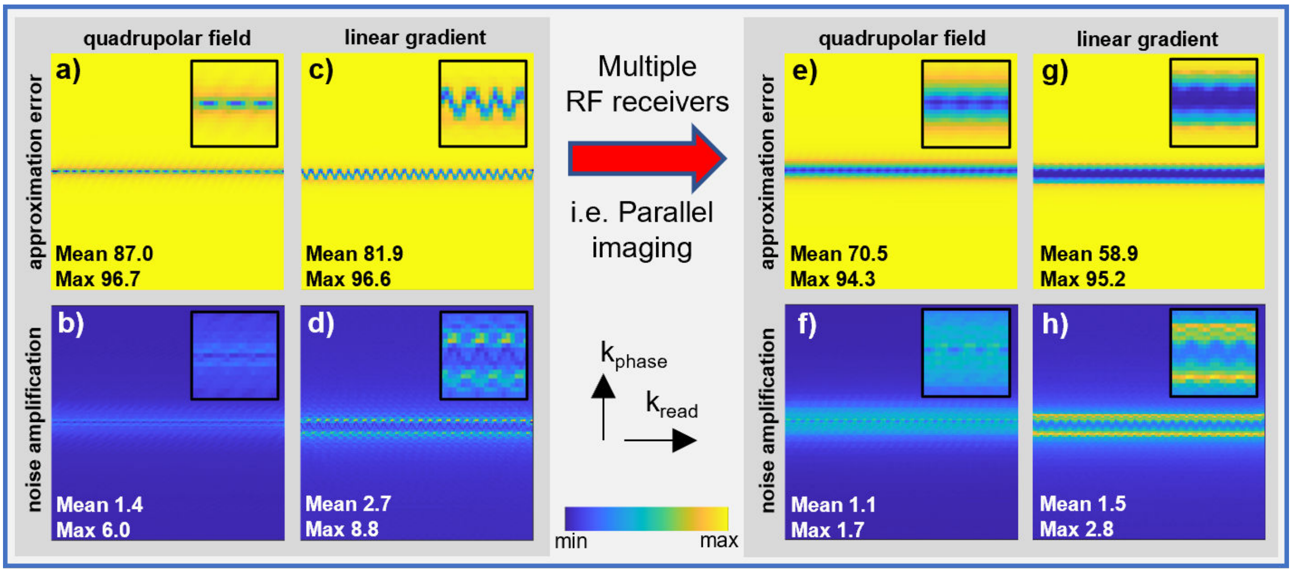
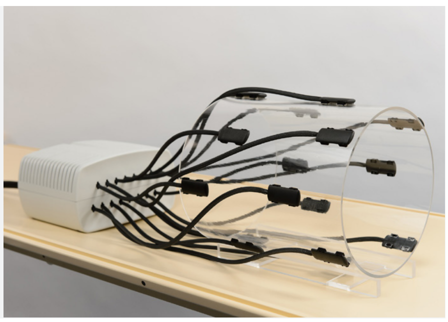


Figure 2: The k-space efficiency maps (i.e., the approximation error and the noise amplification) comparing 2D FLASH scans (one phase encoded step shown) with two distinct B_0 field modulation schemes – a quadrupolar nonlinear field and a linear gradient field – both produced by our local B_0 coil array. a)-d): The k-space sampling coverage with a single RF receiver. e)-h): The k-space sampling coverage in conjunction with parallel imaging (i.e., with multiple RF receivers).

Conclusion

Based on the extended MRI sampling theory with RKHS, we rigorously compare the encoding efficiency of both linear and nonlinear gradients quantitatively in k-space, and investigate the optimal B_0 field modulation schemes for our setup, significantly accelerating in-vivo 2D Cartesian scans. The field probes will continue to serve as invaluable tools for efficiently and precisely debugging such advanced custom-built gradient systems.



Further reading: Accelerated 2D Cartesian MRI with an 8-channel local B_0 coil array combined with parallel imaging.
R. Tian et al. Magnetic Resonance in Medicine: 2023.