PhysiCal: A rapid calibration scan for B_0, B_1+, coil sensitivity and Eddy current mapping.

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Synopsis

Calibration scans that acquire coil sensitivity, B_0 and B_1+ inhomogeneities information play an important role in enabling modern acquisition and reconstruction techniques. This work proposes a unified, rapid calibration sequence termed Physics Calibration (*PhysiCal*) to obtain accurate B_0, Eddy, B_1+ and coil sensitivity maps. *PhysiCal* utilizes a carefully designed mix of full and variable density sampling acquisitions across echoes with synergistic constrained and eigenvalue reconstruction for robust and accurate recovery of whole-brain B_0, B_1+, Eddy and 32-channel coil sensitivity maps in just 11 seconds at 1 mm x 2 mm x 2mm resolution at 3T.

Introduction.

Calibration scans for coil sensitivity-maps (CSM), B_0 and B_1^+ inhomogeneities information play an important role in enabling modern acquisition and reconstruction techniques. Tremendous progress has been made in improving the accuracy and speed of these scans. For CSM, ESPIRiT[1] and JSENSE[2] have been successful in enabling wide-spread parallel imaging, while for accelerated-EPI, FLEET-ACS[3] and Gradient Echo (GRE) with B_0 field map[4] have provided distortion-matched CSM for robust reconstruction. For B_1^+ mapping, Bloch-Siegart[5] (BS) methods have gained prominence due to its flexibility and robustness, where a recent improvement[6] through k-space under-sampling and constrained-reconstruction has enabled rapid B_1^+ mapping. Moreover, a robust multi-echo general linear modelling (GLM) framework for BS[7] has also been developed that enables robust recovery B_0,Eddy and B_1^+ maps.
Nonetheless, the acquisition of multiple calibration scans for high-resolution coil sensitivity, B_1^+ and B_0 maps can be time consuming, taking $5-10$ minutes for whole-brain coverage. This work proposes a unified, rapid calibration sequence termed Physics Calibration (***PhysiCal***) to obtain accurate B_0, Eddy, B_1^+ and CSM. *PhysiCal* utilizes a modified BS multi-echo GRE acquisition, with a carefully designed mix of full and variable density sampling acquisitions across echoes to provide complementary information. This along with synergistic constrained and eigenvalue reconstructions enable $\sim 50\,\times$ speedup of this calibration scan. Retrospective under-sampling experiments demonstrate robust and accurate recovery of whole-brain B_0, B_1^+, Eddy and $32-$channel coil sensitivity maps in just ***11 seconds*** at $1mm \times 2\,mm \times 2\,mm$ resolution at 3T. Furthermore, preliminary verification of *PhysiCal* is presented through using the rapidly generated B_0 and B_1^+ maps to process high-resolution diffusion-imaging data acquired with accelerated gSlider-EPI[8,9].

Acquisition and Reconstruction.

Figure 1 summarizes *PhysiCal* acquisition. A modified BS, bi-polar, multi-echo 3D-GRE acquisition is used with interleaved, opposite, off-resonant frequencies $(\pm 4\,kHz)$[10], and with multi-echo readouts prior and subsequent to the BS pulse[6] to achieve estimation robustness. The k-space sampling of this acquisition is optimized with:

1. A small fully-sampled $(k_y, k_z) = (16, 16)$ auto-calibrated signal (ACS) in the first echo for ESPRIT-CSM.
2. Independently drawn variable density Poisson-disc sampling across echoes $(\sim 50\times)$.

This ensures that the residual aliasing artifacts of these image echoes after parallel imaging and compressed sensing (PI+CS) reconstruction at very high accelerations are incoherent across echoes and can be robustly read-through during the subsequent GLM parameter fitting (analogous to MRF dictionary fitting).

Figure 2 depicts the reconstruction. ESPIRiT is used to calibrate CSM from ACS of the first echo. CSM is then used to perform an l_1-Wavelet regularized PI+CS reconstruction of highly under-sampled echo data $(\sim 50\times)$. Subsequently, GLM robustly recovers artifact-free B_0 and Eddy from reconstructed echo images (which contain temporally-incoherent residual artifacts). However, GLM cannot recover artifact free B_1^+. To overcome this, B_1^+ is refined using an eigenvalue reconstruction approach inspired by ESPIRiT. Phase of the reconstructed echoes after the negative-offset BS pulse is subtracted from the phase of the reconstructed echoes from the positive-offset BS echoes. The resulting time-series is reshaped into “virtual coils” and passed into ESPIRiT, which recovers the expected smooth underlying B_1^+.

Methods.

Data Acquisition: Fully-sampled $1 \times 2 \times 2\,mm^3$ resolution *PhysiCal* data with 16 echoes (4 before BS) are acquired in 19 minutes and 41 seconds $(\mathrm{TR}:\ 36ms,\ \text{echo-spacing}: 1.25ms)$. Gold standard B_0, B_1^+ and Eddy maps are estimated using GLM and CSM is estimated from the first GRE echo using ESPIRiT.
Acceleration Experiments: Acquired data are retrospectively under-sampled by varying the number of sampled (k_y, k_z) points per echo and the number of echoes. First echo contains 16×16 ACS for ESPIRiT-CSM. B_0, B_1^+, Eddy and CSM are recovered through the procedure outlined above, and are then compared to the gold standard. BART[11] was used for sampling-mask generation, ESPIRiT and PI+CS.
Preliminary Efficacy Verification: To demonstrate the applicability, accelerated parametric maps obtained from *PhysiCal* are used in EPI-gSlider. B_1^+ inhomogeneity is used to mitigate striping artifacts in an EPI-gSlider acquisition. B_0 is used to perform post-processing distortion correction to un-distort EPI.

Results.

Acceleration Experiments: Figure 3 presents results from a selected under-sampled case that achieves good trade-off with respect to speed versus recovered map quality. This constitutes an 11 second *PhysiCal* scan at $48\,\times$ acceleration across 12 echoes. Difference maps with respect to gold standard demonstrate high quality of reconstruction that accurately captures high frequency spatial variations in B_0 and B_1^+ maps. Non-linear eddy current fields between odd-even echoes is also captured that could prove useful in improving EPI ghost-correction (at matched echo spacing) over standard 1D ghost-correction.
Preliminary Efficacy Verification: Results are depicted in Figure 4. B_1^+ obtained from the 11 second accelerated case is successful at mitigating striping artifacts in EPI-gSlider. B_0 is successful at performing post-processing distortion correction to match the EPI image to a distortion-free structural image.

However, it cannot resolve signal in voxel pile-up areas, which would require more data (for example, from a 2-shots blip-up and blip-down EPI).

Discussion and Future Work.

A rapid multi-parametric calibration scan termed *PhysiCal* is proposed and demonstrated to capture accurate high-resolution whole-brain B_1^+, CSM, B_0 and eddy current maps in 11 seconds. This rapid acquisition is achieved through tailored under-sampling and synergistic constrained+eigenvalue reconstruction. Future work includes prospective under-sampling implementation and evaluation at ultra-high field with along with utility in pTx B_1^+ calibration. It is expected that the increased B_1^+ variations in these applications will still be captured well by the eigenvalue approach given that ESPRiT successfully estimates B_1^- for local coil arrays. More advanced reconstruction approaches through low-rank and phase-constraints will also be explored to aid an even faster and robust calibration scan. Additionally, the efficacy of *PhysiCal* will be verified on other applications including spatio-temporal encoding like EPTI[12] and MR fingerprinting[13].

Acknowledgements

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Figures

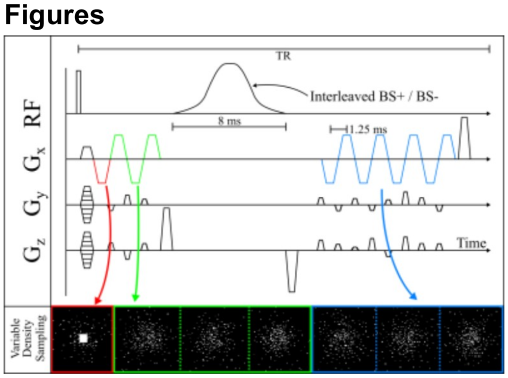

Fig 1: A multi-echo GRE sequence is modified to play a strong, Gaussian-shaped, off-resonant RF frequency pulse (denoted BS) after four echoes. The BS pulse is played at alternating opposite off-resonant frequencies $(\pm 4kHz)$, denoted as $BS+/BS-$. Each echo is sampled according to an independently drawn variable density Poisson-disc distributed sampling mask, with the first echo consisting of a densely sampled ACS region.

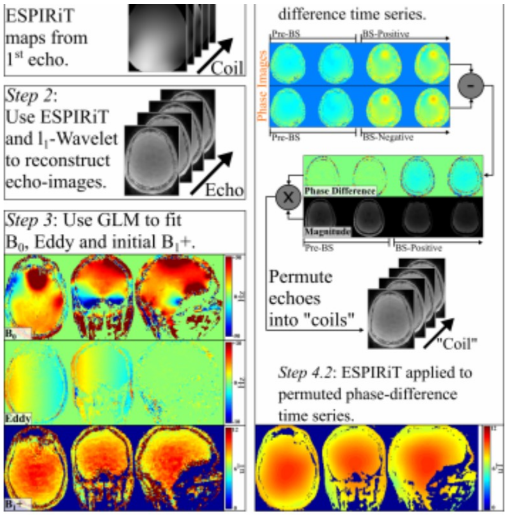

Fig 2: First, ESPIRiT is estimated from the ACS of the first echo. Next, PI+CS with spatial Wavelet reconstructs the highly accelerated echo-images. Note that, while artifacts are still present, they are incoherent over time. GLM robustly recovers B_0 and Eddy maps, but not B_1^+. Next, the phase of reconstructed echoes from $BS-$ is subtracted from the phase of the reconstructed echoes from $BS+$. The resulting time-series is then reshaped into “virtual coils” and passed into ESPIRiT, which recovers the expected smooth underlying B_1^+.

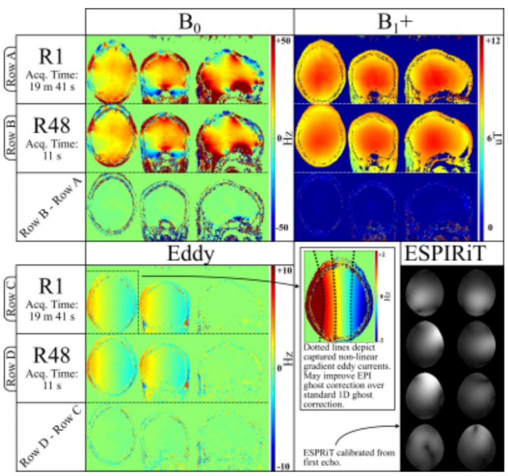

Fig 3: This figure compares the accelerated parametric maps (R48) to the gold standard (R1). By designing tailored under-sampling and using synergistic constrained+eigenvalue reconstruction, accurate and high resolution B_0, Eddy, B_1^+ and coil sensitivity maps can be recovered in 11 seconds.

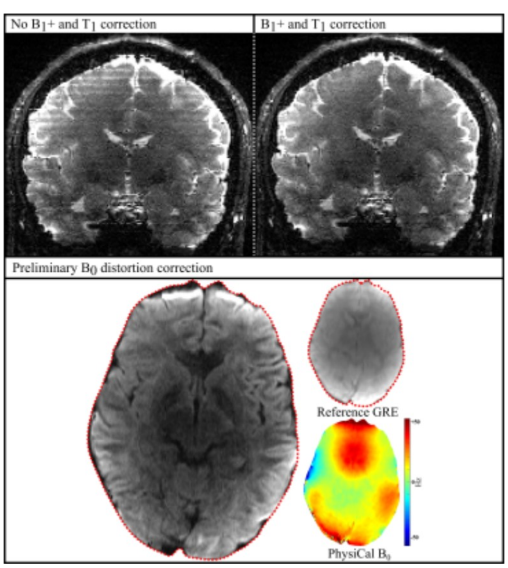

Fig 4: Preliminary applications of *PhysiCal*. B_0 and B_1^+ maps are recovered from a 11-second Physical scan. B_1^+ is able to mitigate striping artifacts in EPI-gSlider acquisition. B_0 is successful at performing post-processing distortion correction to undistort the EPI image to match a distortion-free structural image. However, as expected, it is not able to resolve signal in the voxel pile-up areas, which would require more data (for example, from a 2-shots blipped-up and down EPI).