Optimising for Eddy Currents in Compressed Sensing Spiral Acquisitions

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Target Audience

Scientists concerned with accelerated non-Cartesian sampling strategies and image reconstruction.

Purpose

Accelerating the signal acquisition has been amongst the hottest topics in the entire history of MRI research. While the geometric reality of MR devices and the mechanical and electrical envelope of operation of the gradient encoding favour non-Cartesian sampling one generally can obtains higher SNR per unit time. A more recent development, Compressed Sensing [1,2] has been one of the most valuable contributions to MRI acceleration. It is a most logical and has been suggested in the original publication step to combine both concepts. Generally, when such acquisitions are implemented, the challenge, which is met, is to get the best possible SNR while attaining as high a degree of randomness of data sampling as possible. However, another aspect which needs addressing and has remained in the dark is that of considering a third very important aspect, namely that of random-sampling induced Eddy-currents. While gradient pre-emphasis works quite well for traditional k-space sampling, non-Cartesian trajectories exhibit less benign behaviour.

Theory

$$H_e(s) = 1 - \sum_{i-1}^{N} \frac{\beta_i s}{s + \omega_i'}$$

According to [3], Eddy-current amplitudes are in good approximation a function of slew-rate (step function, s) amplitude. Laplace transformation of the gradient waveform (generally cut off to a few first 3 terms for computational feasibility) reveals the Eddy current transfer function H_e (Eq.1). To reduce the generation of the Eddy currents to the unavoidable for k-space sampling, one should keep the changes to the gradients as subtle as possible. Consideration of transfer function for trajectory design should be performed at all times for Non-Cartesian trajectories.

Methods

A focus was put for this work on the workhorse, spiral trajectory, and its optimisation of for as little additional Eddy-currents as possible by penalising the 2-norm of the transfer function over the length of the readout. To favour the constraint, arguably one should distribute the randomness over as much acquisition k-space as possible while sparing the centre for high SNR dense sampling. Spirals turn out to be particularly well suited for CS in general: 1. High SNR (centre out sampling in every shot). 2. The SR limited range is the optimal range where one introduces randomness without penalty; the remaining range is the challenging part. Summing all of the above the trajectory design is most readily and best achieved by randomly varying the FOV during the acquisitions. Additionally and simultaneously, one may penalise in the optimisation cycles the side peak amplitudes of the point-spread-function, PSF (Fig.3). Such an optimisation run delivers a function for FOV of the current sampling as a function of for example k-space radius.

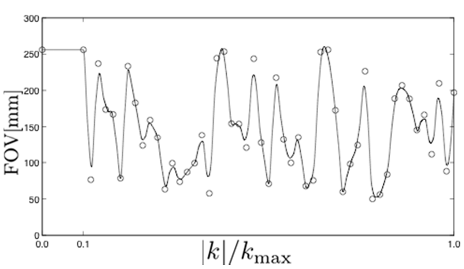

Figure 2: Randomness of sampling for trajectories B and C was achieved through random fluctuation of the field of view of the spiral trajectory.

Results

Data was scanned with an originally 6 shot spiral TSE sequence with 12ms readouts per shot. The trajectory was accelerated with the FOV scheme of Fig 2 in CS direction with a factory of 2.0 (Fig.1B). SENSE-acceleration (Coherent Nyquist violation) was further achieved by skipping 2 of 3 spiral shots (Fig.1C). The reconstructed images shows very nice contrast while artefacts cannot be detected by visual inspection. Comparison with the non-accelerated acquisition shows visibly, however, a less burred image with shorter trajectories.

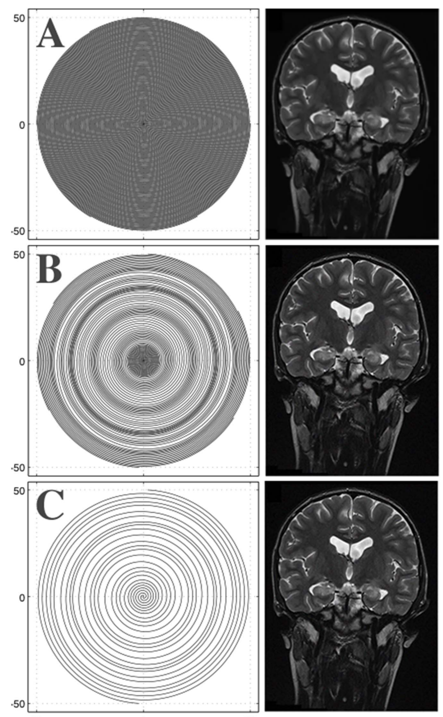

Figure 1: Trajectories for image acquisition along with the reconstructed images. A: Full sampling, 6 shots of 12ms. B: CS R=2.0, 6 shots of 6ms. CS+SENSE R=6.0, 2 shots of 6ms. Differences cannot be seen by visual inspection.

Conclusions and Discussion

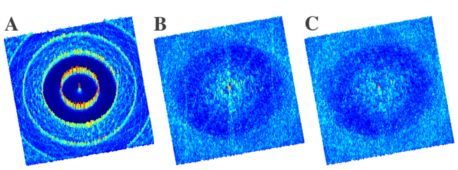

Figure 3: Depiction of PSFs of the accelerated spiral (A), CS spiral as suggested in [2](B) and the proposed spiral trajectory (C). The proposed spiral does not jeopardies the noise like nature of the PSF.

Compressed Sensing allows one to get more out of the acquisition window without the need for additional hardware as opposed to parallel MRI. Its combination with non-Cartesian sampling is of great benefit as is can shorten individual readouts for less blurring. However, one must consider Eddy currents for trajectory design for gains to be sustainable. For spiral trajectories random variation of the FOV seems to work best both for better Eddy-current behaviour as well as favourable PSF.

References

[1] Lustig et al. (2007) MRM 58, p1182 [2] Lustig et al. (2008) IEEE SP 72, p72 [3] Morich et al. (1988) IEEE TMI 7, p247