ESPIRiT Reconstruction Using Soft SENSE

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Introduction: Recently, a new technique to estimate sensitivity maps from auto-calibration signal (ACS) data has been proposed (ESPIRiT)[1]. In the ideal case, this technique yields a single set of sensitivity maps, which can be used in SENSE[2]. For data that is corrupted (by motion, chemical shift, aliasing, ghosting, etc), the SENSE model using a single set of smooth sensitivity maps is inconsistent and often yields additional artifacts. GRAPPA and SPIRiT are more tolerant since they use a relaxed model of implicit sensitivities. For corrupted data ESPIRiT often yields multiple sets of maps in an attempt to fit the data into a subspace. Here, we propose a "soft" SENSE reconstruction for ESPIRiT, which uses multiple weighted sets of maps. This has similar robust reconstruction properties as SPIRiT and GRAPPA but allows better flexibility in the reconstruction.

Theory: Autocalibration methods can be formulated in terms of a calibration matrix, which is constructed from ACS data. Its nullspace encodes correlations between channels and neighboring points in k-space. Using this information, coil sensitivities can be estimated in the image domain as eigenvector maps from a point-wise eigendecomposition of a related operator[1]. In case of corruption, additional eigenvalues appear which correspond to signal components not consistent with a single set of maps, e.g. aliasing due to motion, chemical shift, ghosting or a small FOV. While these are implicitly taken into account in SPIRiT, they cause problems in SENSE yielding additional artifacts due to motion inconsistency. Extending SENSE to use multiple maps (ESPIRiT), one can design more robust "soft" reconstruction algorithms:

$$\varphi(x_1,...,x_n) = \sum_i \left\| P_k DFT \sum_j c_{ij} x_j - y_i \right\|_2^2 + \alpha R(x_1,...,x_n) \quad e.g. \quad R(x_1,...,x_n) = \sum_j \left\| x_j \right\|_2^2 \quad or \quad \sum_j \left\| W x_j \right\|_1^2$$

Here, c_{ij} are M sets of N sensitivity maps, x_j are multiple images, y_i the data, DFT is the discrete Fourier transform, P is the sampling operator, and R is regularization term weighted by α and optionally using a sparsity transform W. Using only one set of maps corresponds to SENSE, while using all maps removes all parallel imaging constraints and the ability to accelerate. Ideally, one should use the right number of maps at each pixel corresponding to the eigenvalues above a certain cut-off, but this might cause truncation artifacts around image regions with different number of maps. Instead, we propose to use a set of maps weighted by a function of the eigenvalue maps $v_j(x)$ according to $\sigma\left(\left(\sqrt{v_j}(x) - a\right)/(1-a)\right)c_j(x)$ with cut-off parameter a and σ being a smooth s-curve transition between zero and one. We call this a soft-SENSE reconstruction for ESPIRiT.

Methods: Data from a 3D fast spin-echo MRI (TR/TE = 1,600/20.8 ms, 37 echos, matrix size: 320 × 288 × 236, acceleration 8.4 with VD Poisson-disc sampling) of a human knee has been processed with ESPIRiT (size of calibration region: 24 , kernel size: 6) to obtain maps. Images have been reconstructed with the proposed soft-SENSE reconstruction (a = 0.8), SENSE using the first set of maps and SPIRiT. L1-wavelet regularization was used in all methods.

Results and Discussion: Figure 1 shows the maps of the first four eigenvalues. Due to motion corruption, the second map has areas with high eigenvalues and ESPIRiT produces two images. Figure 2 compares different reconstructions: L1-SENSE (1 map) yields images with severe motion artifacts, while the use of two maps (L1-ESPIRiT) allows a reconstruction with reduced artifacts similar to L1-SPIRiT.

Conclusion: The proposed soft-SENSE implementation of ESPIRiT achieves a smooth transition between image regions with inconsistencies where additional signal components appear, while constraining the solution to the strict SENSE-model in regions without inconsistencies.

eigenvalues   L1-ESPIRiT 1   L1-ESPIRiT 2

Figure 1: Motion-corrupted scan of a human knee. The maps of the four highest eigenvalues are shown. In the second map areas with high eigenvalues appear due to motion corruption. Using two sets of sensitivity maps weighted by a function of the eigenvalue maps, L1-ESPIRiT with soft SENSE yields two images which capture all signal components.

L1-SENSE   L1-SPIRiT   L1-ESPIRiT

Figure 2: Motion-corrupted scan of a human knee. L1-SENSE uses only a single set of maps and yields a corrupted image. L1-ESPIRiT with soft-SENSE reconstruction produces a combined image with reduced artifacts similar to L1-SPIRiT.

References: 1. Uecker M, Peng L, Murphy JM, Virtue P, Elad M, Pauly JM, Vasanawala SS, Lustig M. ESPIRiT – An Eigenvalue Approach to Autocalibrating Parallel MRI: Where SENSE meets GRAPPA. Magn Reson Med 2012; Submitted. **2.** Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: Sensitivity encoding for fast MRI. Magn Reson Med 1999; 42:952–962. **3**. Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, Wang J, Kiefer B, Haase A. Generalized autocalibrating partially parallel acquisitions (GRAPPA). Magn Reson Med 2002; 47:1202–1210. **4**. Lustig M, Pauly JM. SPIRiT: Iterative self-consistent parallel imaging reconstruction from arbitrary k-space. Magn Reson Med 2010; 64:457–471.