2D-SENSE for Simultaneous Multi Slice Imaging

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Introduction: Parallel undersampled simultaneous multi-slice (SMS) imaging[1,2] has recently gained popularity, especially for 2D single-shot sequences like EPI, where in-plane parallel imaging only results in marginal reductions of volume TR. The initial demonstrations of SMS-EPI[2] use a SENSE/GRAPPA[3] approach to separate the slices. (blipped-)CAIPIRINHA[1,4] for SMS acquisitions is generally preferred since it reduces g-noise, however it is incompatible with SENSE/GRAPPA: sharp signal discontinuities arise when concatenating the FOV-shifted reference slices to form the SENSE/GRAPPA calibration data, causing phase errors in the reconstructed image[1]. As a solution, Setsompop[1] has proposed a multi-kernel GRAPPA method ("slice-GRAPPA") where a separate kernel is fitted for every slice. Crucially (with the exception of a recent work by ref [5]), most SMS reconstructions employ a two-step approach to first disentangle the aliased slices, and then perform in-plane parallel reconstruction, or vice versa. Here we propose to use 2D-SENSE[5] reconstruction for simultaneously excited slices, as a general one-step approach to reconstruct SMS data with arbitrarily undersampled Cartesian k-space in phase and/or slice directions.

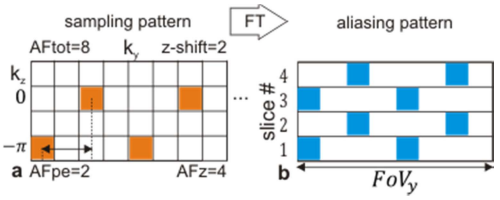


Fig 1. Sampling pattern (AF_{pe}=2, AF_z=4, shift 2) and 2D-SENSE aliasing pattern corresponding to reconstruction in Fig 3.

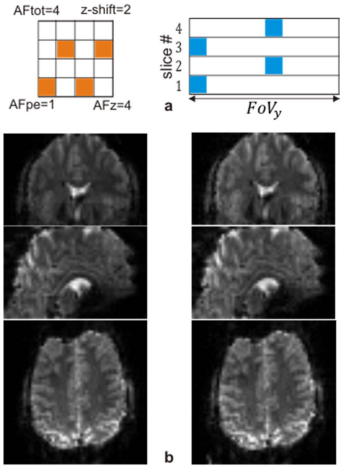


Fig 2. SMS-EPI (AFpe=1, AF_z=4, shift 2) with matrix 64x64, 36 slices. Left: Slice-GRAPPA, Right: 2D-SENSE recon. The sampling and aliasing patterns are shown in a).

Theory: The motivation for 2D-SENSE reconstruction becomes obvious when adopting a 3D k-space representation of the SMS sampling process as described in ref [5] and [7]. The read direction is fully sampled, so the two phase encode directions (in-plane and slice direction) form a 2D reconstruction problem that is entirely equivalent to that of volumetric CAIPIRINHA[4]. Given an undersampled k-space, the resulting image aliasing pattern is obtained by the Fourier Transform of the sampling pattern, with zeros and ones denoting skipped and acquired samples, respectively[4]. This is illustrated in Fig 1. For practical purposes, the aliasing pattern directly provides the matrix indices of the aliased voxels that have to be separated, which allows for a most general and convenient implementation of the 2D-SENSE algorithm. Fig 1 shows an example for four simultaneously excited slices (AF_z=4), factor-2 in-plane undersampling (AF_{pe}=2) and CAIPI-shift $2\Delta k_z$. The SENSE aliasing pattern in Fig 1b has AF_{tot}=2x4=8 non-zero entries where the y-axis scales with the resolution. If the CAIPI-shift is not an integer factor of the nominal k-space increment as defined by the FOV spanning the multiple slices (e.g. AF_z=8, CAIPI-3), this corresponds to non-integer factor undersampling (8/3) and an "extended FOV reconstruction" can be applied: "dummy slices" with zero intensity are added to reformulate the problem with integer-factor undersampling, e.g. for AF_z=8, CAIPI-3, adding one dummy slice (gray) creates an AF_z=9, CAIPI-3 problem that becomes trivial to solve with Cartesian SENSE (Fig 4a).

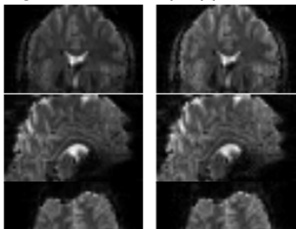
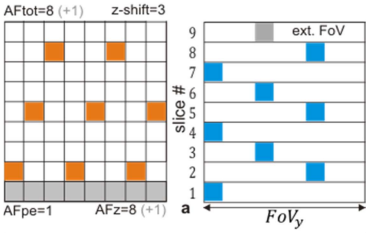


Fig 3. SMS-EPI (AFpe=2, AF_z=4, shift 2) with matrix 96x96, 36 slices. Left: Slice-GRAPPA, Right: 2D-SENSE



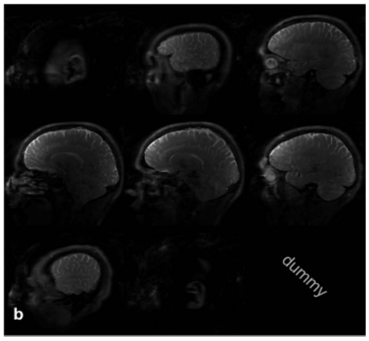


Fig 4 a) extended FoV aliasing pattern (AF_{pe}=1, AF_z=8, CAIPI-3) and b) 2D-SENSE recon of 8 simultaneous slices acquired slices a PINS SMS-TSE sequence[8].

Methods: We show three examples of SMS reconstruction with 2D-SENSE. Two single-shot blipped-CAIPI SMS-EPI acquisitions at 7T with (a) matrix 64x64, 3.75x3.75x2.5mm^3 voxels, 36 slices in 9 SMS slice groups, AF_z=4 , AF_{pe}=1, CAIPI-factor 2, slice separation d=20mm and (b) matrix 96x96, 2.5mm isotropic voxels, 36 slices in 9 SMS slice groups, AF_z=4 , AF_{pe}=2, CAIPI-factor 2, slice separation d=20mm; as well as (*c*) an SMS TSE/RARE acquisition at 3T with PINS[8] multi-slice excitation (matrix 256x256, 56 slices in 7 SMS-slice-groups, AF_z=8, AF_{pe}=1, CAIPI-factor 3, slice distance d=21mm, 8 shots with ETL=32). In each case, coil sensitivity maps were derived from fully sampled short-TE-TR low resolution GRE scans covering the acquisition volume, and using adaptive coil combination. For comparison, the data were also reconstructed using a 3x4 sliceGRAPPA kernel (followed by 3x4 GRAPPA in case of the in-plane undersampled EPI).

Results: Figs 2 and 3 show the 64x64 and the 96x96 blipped-EPI reconstructions with slice-GRAPPA (left column) and 2D-SENSE (right), as well as the corresponding sampling and aliasing patterns. Fig 4 shows one SMS slice group of the extended FoV 2D-SENSE reconstruction of the TSE data. The added dummy samples and slices facilitate integer SENSE recon and are indicated in gray.

Discussion: We have shown that a 2D-SENSE approach can be used to reconstruct SMS acquisitions with CAIPI-like sampling patterns. A 2D-SENSE approach is conceptually simple and easy to implement. In case of additional in-plane undersampling it provides a one-step reconstruction along both undersampled dimensions which conceivably is numerically more stable than a two-step approach. It also provides a "contrast independent" parallel imaging reconstruction by using actual coil sensitivity maps.

References

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