The Combination of 2D SENSE and 2D Partial Fourier Homodyne Reconstruction: Achieving Acceleration Factors Greater Than the Number of Coils

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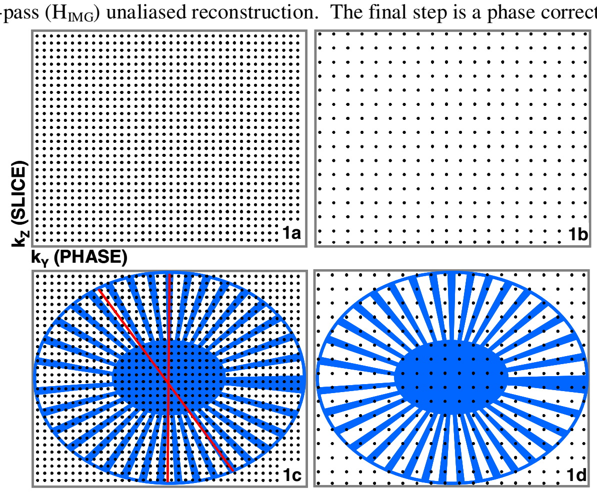
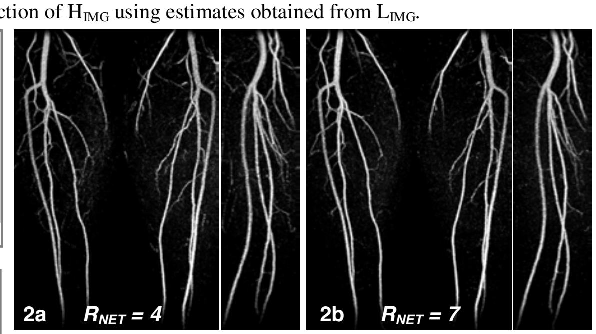
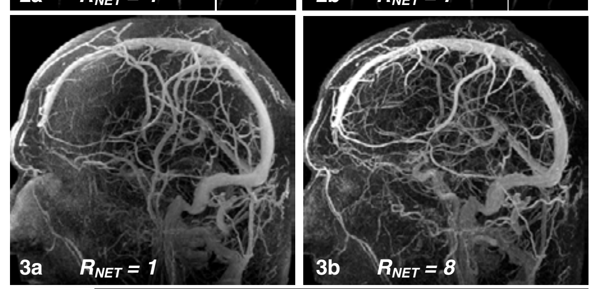
INTRODUCTION Sensitivity Encoding (SENSE) has gained acceptance in many MR applications. While the upper limit of the SENSE factor *R* is bounded by the number of coil elements used, typical *R* values are smaller as a consequence of unfavorable coil geometries. In this work, we demonstrate a method where acceleration factors exceeding the number of available coil elements can be reliably obtained with diagnostic quality images in *in vivo* 3D MRI. This is achieved by combining 2D SENSE with 2D partial Fourier (PF) and homodyne (HD) reconstruction. One-dimensional PF is commonly used to shorten TE or reduce scan time. Approaches include shortened asymmetric echoes or near-half sampling along either the phase or slice encoding directions. Recently, a modified elliptical centric (EC) view order was developed to improve speed and spatial resolution performance in 3D contrast-enhanced MR angiography (CE-MRA) **[1]**. It exploits two-dimensional PF by undersampling both k_Y-phase and k_Z-slice encoding directions simultaneously, yielding robust near two-fold accelerated images. Previous work **[2]** has proposed combining SENSE with 1D-PF in 2D imaging. The purpose of this work is to incorporate the aforementioned 2D-PF strategy with robust 4-5× 2D-SENSE **[3]** for fast 3D imaging. This integration allows the absolute acceleration factor of SENSE-PF to be significantly greater than what each technique (i.e. SENSE or PF alone) can provide separately. A seven-fold net acceleration was achieved for a four-coil configuration, and greater than eight-fold reduction for an eight-coil array. The hypothesis is tested in high-resolution 3D CE-MRA of the lower legs and intracranial vasculature.

METHODS Fig.1 compares the k_Y-k_Z plane of (a) non-accelerated reference, (b) 4× 2D-SENSE, (c) 1.7× 2D-PF with 2D-HD, and (d) > 7× combined 2D SENSE-PF acquisition strategies. It is drawn for illustration clarity, with a reduced number of echoes. Black dots represent frequency-encoded full echoes on a Cartesian grid. Fig. 1c shows the 2D-PF technique. Only views located within the blue k-space sampling footprint are acquired. The footprint contains a central ellipse and an outer annulus consisting of multiple sectors. All views are acquired in an EC manner, starting with the central ellipse. This is followed by collection of anti-symmetric sectors across the k_Y-k_Z plane in the outer annulus. Thus a sampled ($+k_Y$, $+k_Z$) view does not have its conjugate ($-k_Y$, $-k_Z$) sampled (red lines). 2D-HD is used to account for the non-sampled sectors by using phase information obtained from the central region. The speed-up of 2D-PF (c) over (a) is 1.7×, versus only a 1.2× savings had partial echo been applied along k_X in (a). The 2D-PF footprint was adopted for the EC view order and takes advantage of projection reconstruction-like sampling, which has been shown to be robust against artifacts **[4]**. Fig. 1d shows the merger of 2D-SENSE with 2D-PF. The resultant k-space is significantly undersampled compared to (a).

A specific reconstruction algorithm was developed to account for data that must undergo both 2D-SENSE unfolding and 2D-homodyne processing. Raw data from each coil are first Fourier transformed along the readout axis. They are then directed along two paths: a low-pass filter (central ellipse only), and a high-pass filter (ellipse + 2× anti-symmetric sectors). After Fourier transforms along Y and Z, low and high-pass data are then separately unfolded with SENSE, yielding a single low-pass (L_{IMG}) and a single high-pass (H_{IMG}) unaliased reconstruction. The final step is a phase correction of H_{IMG} using estimates obtained from L_{IMG}.







All studies were approved by our institution and conducted on 1.5T GE Signa and Excite scanners. Table 1 summarizes parameters. Spatial resolution values are truly-acquired and not zero-fill interpolated. All results were evaluated by radiologists for quality and diagnostic capability.

RESULTS High-quality images were obtained from both 2D-SENSE and 2D SENSE-PF strategies in all lower leg and intracranial volunteers. Fig. 2 illustrates an example from the lower leg studies. Coronal and sagittal views from a 34 sec 4× 2D-SENSE scan are shown in (a). Images of the same volunteer using a 19 sec 7× 2D SENSE-PF acquisition (b) show comparable spatial resolution and vessel enhancement. A maximum SENSE speed-up of four was achieved with a minimum of four coils. Additional acceleration with 2D-PF did not compromise image quality. Fig. 3 shows an example of whole-brain venography. An eight-element array was used to achieve 4× 2D-SENSE acceleration. Sagittal projections from (a) non-accelerated 6 min 20 sec and (b) 47 sec 2D SENSE-PF acquisitions are shown. The SENSE-PF image exhibits excellent image quality and better enhancement of sagittal sinuses and cerebral veins compared to reference, despite 8× shorter scan time.

TABLE 1	Lower Leg	Intracranial
Number of Studies	23	11
Number of Coils	4 rectangle	8-channel head
FOVx, y, z (cm)	44, 26-30, 8.8-12.3	25, 25, 16-17
Nx, Ny, Nz	256-384, 256, 88	320, 320, 124-176
Δx, Δy, Δz (mm)	1-1.5, 1-1.2, 1-1.4	0.8, 0.8, 1-1.4
SENSE Acceleration	4	4-5.2
SENSE-PF Acceleration	7	7-8.2
SENSE-PF Acq. Time (s)	19-24	30-47

CONCLUSION 2D SENSE-PF can significantly improve performance in 3D CE-MRA. The technique yields diagnostic-quality images from extensively undersampled k-space, and can reliably achieve greater accelerations that are beyond the number of coils used.

[1] Madhuranthakam AJ. ISMRM 2004:8. **[2]** King KF. ISMRM 2000:153. **[3]** Weiger M. Magma 2002;14:10-19. **[4]** Peters, DC. MRM 2000;43:91-101.