A Method to Combine Compressed Sensing with Auto-Calibrating Parallel Imaging Reconstruction for Cartesian Acquisition

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INTRODUCTION: Auto-calibrating parallel imaging (acPI) [1,2] is a well-developed technique that has superior performance to image-space PI methods [3] when accurate coil sensitivity maps are difficult to obtain. Compressed sensing (CS) [4] is an emerging acceleration technique that is based on the sparsity of images. Different approaches have been proposed to combine CS with acPI to achieve higher acceleration factor. Lustig et al. presented an L1-SPIRiT method that utilizes a Poisson-disc sampling pattern and an acPI-like self-consistency operator, and iteratively applies this operator and the CS operator [5] in reconstruction. King et al. proposed a two-step undersampling scheme. In reconstruction, CS is performed on coherently wrapped images, and the acPI operator is applied after the completion of CS and thus is not included in the iterative process [6]. Here we present an approach that synergistically combines CS with acPI. This approach uses the same two-step sampling strategy [6,7]; however, different from Ref. [6], a conventional acPI operator is included in the iteration of the reconstruction and CS is performed on unfolded images.

THEORY **Sampling**: 3D k-space is undersampled in the ky-kz plane in two steps as shown in Fig. 1. Step (a): A conventional acPI undersampling scheme, i.e. outer k-space is uniformly undersampled (here by 2×2). Step (b): The uniformly accelerated outer k-space is further undersampled either randomly [4] or pseudorandomly (such as Poisson-disc [5] or IVD [8]).

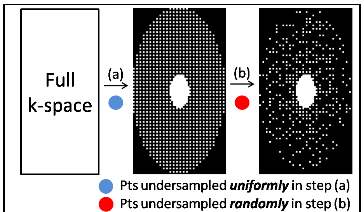

Fig. 1. Undersampling strategy.

acPI calibration: In the proposed method, the acPI is calibrated for a uniformly undersampled pattern and an acPI synthesis operator ***G*** can be generated, shown in Fig. 2. Previous work [7,9] showed that even with the two-step undersampling, the application of ***G*** is capable of efficiently suppressing the coherent (parallel imaging) aliasing artifacts and leaving incoherent (further undersampling) aliasing artifacts to be addressed by constrained reconstruction (CS in this work).

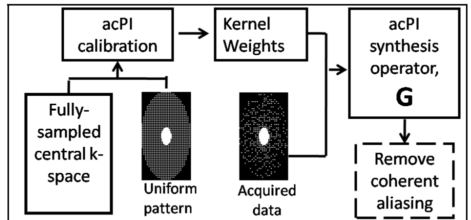

Fig. 2. The acPI synthesis operator **G** is generated by performing acPI calibration for a uniformly undersampled pattern.

Reconstruction: In each iteration, after the acPI operation, CS is applied on the unaliased images to update the randomly undersampled points (red points in Fig. 1), and then the updated red points along with sampled points are used to synthesize the uniformly undersampled points (blue points) using acPI. Ideally, when the red points are fully recovered by CS, the acPI operator ***G*** will fully recover all blue points. The combined method can be performed in the following steps, shown in Fig. 3. (i) Apply ***G*** on the zero-filled density-compensated k-space data followed by FFT. (ii) Perform L1 norm minimization on the resulting image. (iii) The image is then transformed back to k-space and data consistency is enforced by a data replacement process. (iv) Apply ***G*** on the updated k-space data and then FFT. (v) Repeat step (ii) through (iv) until convergence. Here Total Variation (TV) was chosen as the sparsifying transform and negative gradient descent was used for minimization. Alternatively, other sparsifying transforms such as wavelet and other optimization methods (soft-threshold, nonlinear-conjugate-gradient, etc.) can be applied.

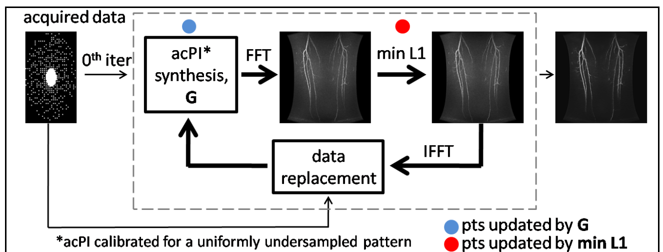

Fig. 3. Reconstruction Diagram. The missing k-space points (both blue and red) are updated within the iterations (gray dashed box).

MATERIALS AND METHODS: The proposed method was applied using two 3D time-resolved contrast-enhanced MR angiography (CE MRA) exams of the calves acquired on a 3T clinical MRI scanner (GE Healthcare, Milwaukee, WI, USA). Imaging parameters included a matrix size of 512 (freq) × 360 (phase) × 68 (slice) over an FOV of 48 (S/I) × 33.8 (L/R) × 12.9 (A/P) cm^3 for a native resolution of 0.94 × 0.94 × 1.9 mm^3. An 8-channel Torso coil was used and a parallel imaging reduction factor of 4 was prescribed, with R=2 along both L/R and A/P directions. An IVD [9] scheme was used to further pseudo-randomly undersample the outer k-space by an additional factor of 4 (total of 16). In reconstruction, ARC [2] was used as the acPI reconstruction method, and a 3D kernel of size $W_x \times W_y \times W_z = 3\times5\times5$ was used.

RESULTS AND DISCUSSION: Fig. 4 shows a comparison between the zero-filled acPI method and the CS with acPI method. First note that the zero-filled acPI method (Fig. 4(a)) does not have apparent coherent aliasing, which suggests that the operator ***G*** is able to suppress parallel imaging artifacts. The CS with acPI method shows improved image quality and no coherent aliasing artifacts are observed in both coronal and sagittal (Fig. 4(b) and (c)) planes. In the zoomed images in the white box area, the proposed method (Fig. 4(e)) shows superior depiction of the secondary branching vessels that are otherwise lost or poorly visualized in the zero-filled reconstruction (Fig. 4(d)).

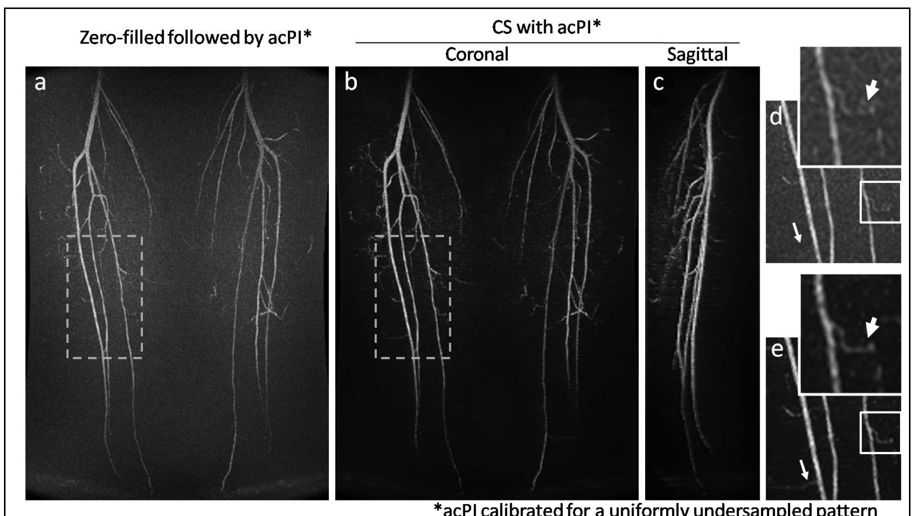

Fig. 4. Images reconstructed using zero-fill acPI (a) and CS with acPI (b,c). The proposed CS with acPI (e) method provides better visualization and depiction of small vessels (arrows) than the zero-filled method (d). No coherent wrapping artifacts are observed in all images.

CONCLUSIONS: In this work, a novel method that combines CS with acPI reconstruction was presented and its feasibility was investigated. Noise reduction and improved depiction of small arteries were observed in *in-vivo* CE MRA exams.

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REFERENCES [1] Griswold et al., MRM 2002;47:1202 [2] Brau et al., MRM 2008; 59:382 [3] Pruessmann et al., MRM 1999;42(5):952 [4] Lustig et al., MRM 2007; 58:1182 [5] Lustig et al., ISMRM 2009, p379 [6] King et al., ISMRM 2010, p4881 [7] Wang et al., ISMRM 2010, p352 [8]Busse et al., ISMRM 2009, p4534 [9] Busse et al., MRA Club, 2010, P.11