Interleaved Variable Density Sampling with ARC Parallel Imaging and Cartesian HYPR for Dynamic MR Angiography

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INTRODUCTION

For MR applications such as contrast-enhanced MR angiography (CE-MRA), it is desirable to simultaneously achieve high spatial and temporal resolutions; however fully-sampled Cartesian acquisition of large matrices is time consuming. View sharing combined with parallel imaging (PI) improves temporal resolution [1], as does incoherent under-sampling with compressed sensing (CS) [2] or Cartesian HYPR reconstruction [3,4]. Here, we describe how ARC parallel imaging [5] and HYPR can be used in combination to robustly reconstruct high temporal and spatial resolution images from highly under-sampled Cartesian data and show *in vivo* feasibility results for lower extremity CE-MRA.

MATERIALS AND METHODS

The proposed method, explained in Fig. 1, is based on the hypothesis that ARC can be used to remove coherent artifacts due to regular parallel imaging undersampling, leaving only incoherent artifacts that are addressed by HYPR. Expressed mathematically, final HYPR image is calculated as

$$I_H = I_C \cdot \frac{I_t}{I_C^t} \qquad \text{Eq.(1)}$$

$$= FT[ARC(K_C)] \cdot \frac{FT[ARC(K_t)]}{FT[ARC(K_C \cdot S_t)]}$$

The proposed method was applied to image the calves of 7 volunteers in a CE-MRA feasibility study on a 3T clinical MRI scanner (GE Healthcare, Milwaukee, WI, USA). Typical imaging parameters included a matrix size of 512 (freq) x 298 (phase) x 70 (slice) over an FOV of 48 (S/I) x 27.9 (L/R) x 12.6 (A/P) cm^3 for a native resolution of 0.94 x 0.94 x 1.8 mm^3. 75% fractional readout, BW=±62.5kHz, TR/TE=5.6/2.0 ms. Twenty-four time frames, resolved at 7.7 seconds, were acquired over 3 minutes. Prior to contrast agent injection, a fully-sampled-full-FOV mask was acquired over 2 minutes and was used for the calibration phase of the ARC algorithm [5]. 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. In reconstruction, a 3D kernel of size $W_x \times W_y \times W_z = 3\times9\times9$ was used for ARC. In HYPR processing, the composite image was generated by averaging data acquired in a sliding window of 12 frames for better SNR.

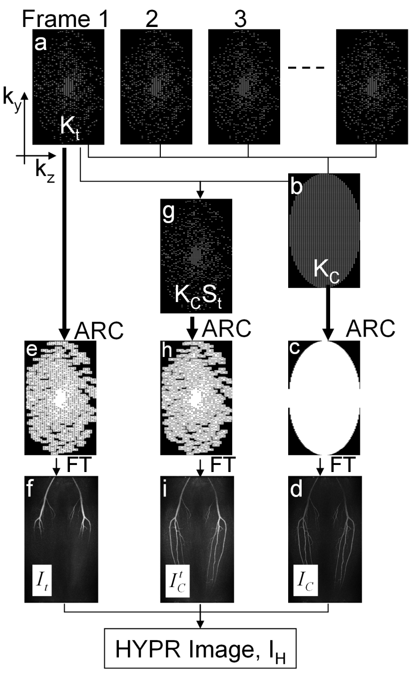

Figure 1. Schematic diagram of the proposed method.
Step 1. A temporally-blurred "composite" image, I_C, is formed (a-d): (a) A uniformly undersampled Cartesian data grid (2×2 parallel imaging acceleration) is further undersampled by a factor of 4 in an interleaved variable density (IVD) pattern [6]. (b) Data from a subset of all the time frames are combined, using a sliding window average to create a composite dataset that has uniform undersampling on the 2x2 acceleration grid, K_C. Minimal sliding window length corresponds to a fully-sampled 2x2 acceleration grid, while larger length can further improve SNR at the cost of increasing the temporal footprint of the composite. (c) ARC is used to synthesize the missing data points. (d) An FFT of these data produces the temporally-blurred composite image, I_C.
Step 2. A temporally-resolved image I_t is also produced from just the data acquired in a single highly undersampled time frame (e-f): (e) For data in each undersampled time frame K_t, ARC is used to synthesize points off the 2x2 acceleration grid. (f) An FFT of these data produce the image I_t, which is unaliased, but has incoherent undersampling artifacts.
Step 3. A subsampled composite image, I^t_C, is also produced for each time frame (g-i): (g) The composite data K_C are subsampled using the IVD pattern for that time frame, S_t. (h) ARC is used to synthesize points off the 2x2 acceleration grid. (i) An FFT of these data produce the image I^t_C, which has the same incoherent undersampling artifacts as I_t. Finally, for each time frame, HYPR is used to form the image I_H (Eq.1).

RESULTS

A combined PI and HYPR acceleration factor of 16 was achieved. Fig. 2 shows the reconstructed images of 3 consecutive time frames, and a sagittal reformat of a single leg. The temporal changes of the vessels are well depicted with high spatial resolution. It is clear that the ARC algorithm can unfold the aliased image that was originally acquired on a reduced-FOV grid. (Reconstruction without ARC, by zero-filling prior to applying the FFT, is shown in inset of Fig.2 (a)).

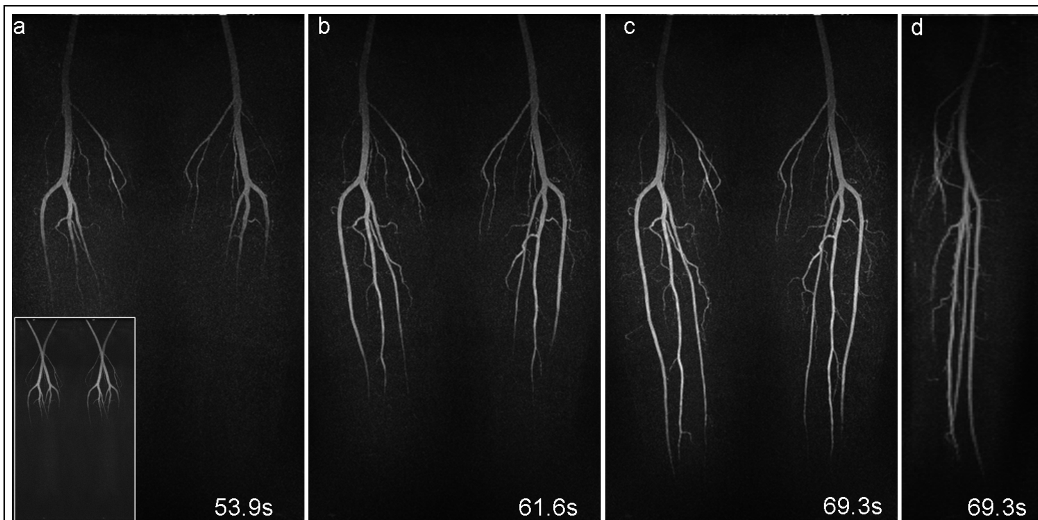

Figure 2. Coronal MIP images (a-c) of 3 consecutive time frames and a sagittal reformat (d) of a single leg shown in (c). The inset in (a) shows an aliased image that was reconstructed without ARC by zero-filling prior to applying the FFT.

DISCUSSION AND CONCLUSIONS

This work demonstrates that parallel imaging can be incorporated into the previously described IVD-HYPR method [3,4,6] to yield a total acceleration factor of at least 16. Feasibility studies in volunteers confirmed coherent aliasing artifacts can be suppressed and high-quality images with simultaneous high temporal and spatial resolution can be produced.

ACKNOWLEDGEMENTS We grateful acknowledge GE Healthcare for their assistance and NIH for funding support.

REFERENCES [1] Haider et al., MRM 2008; 60:749-760 [2] Lustig et al., MRM 2007; 58:1182-1195 [3] Wang et al., ISMRM 2009; p3884 [4] Busse et al., ISMRM 2009; p2834 [5] Brau et al., MRM 2008; 59:382-395 [6] Busse et al., ISMRM 2009; p4534