High-Speed, High-Resolution Whole-Head Sparse Contrast-Enhanced MR Angiography

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Introduction: Contrast-enhanced MRA (CEMRA) has become a standard approach for assessing the vasculature from the aorta to the circle of Willis (1,2). Although the spatial resolution achievable with CEMRA has substantially increased in recent applications (3), in some regions such as in the head, the short arterial-to-venous transit time and the requirement for high spatial resolution remain challenging. In this context, sparse sampling theory (4) suggests that using larger sampling sizes, it should be possible to reach asymptotic incoherence and hence even higher acceleration. In this work, we implemented a highly-accelerated MRA technique with sparse incoherent sampling and iterative reconstruction on a standard clinical MR system and evaluated its performance for whole-head CEMRA of arterial and venous phases.

Materials and Methods: Scanning was performed on 10 consecutive patients scheduled for contrast head MRI on a 3T MR scanner (MAGNETOM Skyra, Siemens AG, Erlangen, Germany) using a prototype sparse CE-MRA sequence and reconstruction. High-spatial-resolution 3D CE-MRA (fast-spoiled gradient-refocused echo sequence; TR/TE: 3.6/1.53 ms; flip angle: 25°; sampling bandwidth: 592 Hz/pixel; field of view: 265 × 232 x 202 mm^3; image matrix: 384 × 336 x 288; resolution: 0.7 mm^3 isotropic) was acquired with a variable-density Cartesian spiral phyllotaxis sampling pattern (5) (Fig. 1) with linear reordering in the phase-encoding plane. The technique was optimized and evaluated in a phantom which consisted of a flexible tube filled with contrast agent and immersed in a water container. A fully sampled dataset of the phantom was acquired and reconstructed retrospectively with: 1) varying undersampling factors, 2) varying regularization factors. In patients, pre- and two post-contrast (arterial and venous phase) measurements following injection of 0.1 mmol/kg of gadolinium were acquired, covering the entire head in just 10 s per 3D volume (16 s including adjustments and ref scan). Inline reconstruction on the clinical MR scanner (Quad-core Xeon 3.2 GHz) was done with a redundant Haar wavelet based L1-regularized iterative SENSE algorithm with a modified FISTA algorithm (20 iterations) (6).

Results: The inline reconstruction of the images took 6 min per 3D volume. The correlation coefficient (R^2) between fully sampled and retrospectively undersampled data consistently decreased with increasing acceleration. Up to an acceleration factor of approximatively 30, the R^2 decrease rate was limited and $R^2 \geq 0.99$. For acceleration factors larger than 30, a faster decrease in R^2 was observed. The regularization vs. R^2 curve presented an unimodal shape. From low regularization factors, R^2 sharply increased up to a maximum with $R^2 \geq 0.99$ for regularization factors between 0.004 and 0.01. Beyond this range, R^2 consistently decreased. Based on the phantom experiments, a 30-fold acceleration and a regularization factor of 0.008 were used for acquisitions in vivo. The sparse CEMRA technique provided whole-head coverage and excellent visualization of the arterial and venous vasculature, including small facial vessels (Fig. 3).

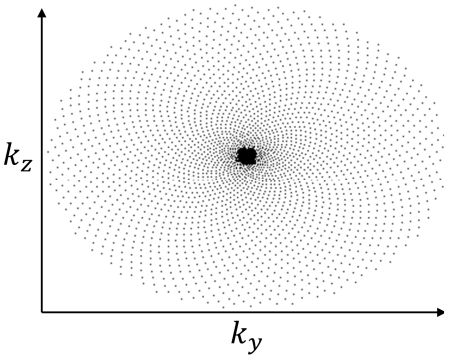

Fig.1: Cartesian spiral phyllotaxis sampling pattern with a 30-fold undersampling.

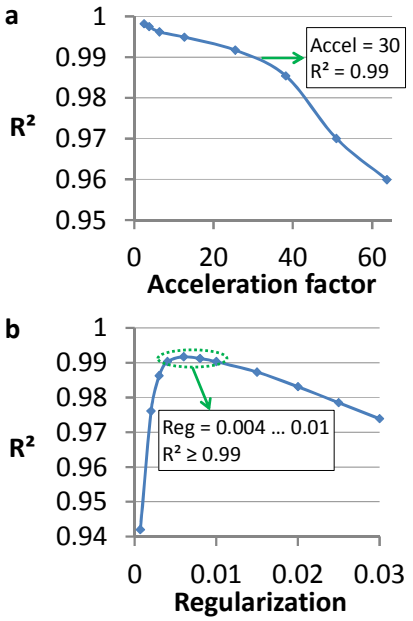

Fig.2: Correlation coefficients of the retrospectively reconstructed phantom datasets against the fully sampled one.

Discussion: While sparse MRI techniques have not yet reached clinical routine, we demonstrated the feasibility of high-quality sparse CEMRA of the whole head on a standard clinical scanner without additional hardware and in a clinical environment. Sparse CEMRA provided high-resolution images in short acquisition times beyond what is feasible with conventional MRA techniques. These promising results are consistent with the theoretical considerations that indicate the potential of sparse MRI for applications with high CNR and large matrix sizes (7). Our results confirm the hypothesis that sparse MRI can be used to increase spatial resolution which in turn increases asymptotic incoherence and sparsity and eventually allows even higher acceleration factors (4,8,9). While further clinical studies are needed to evaluate the diagnostic value of sparse MRA, these initial results indicate the clinical potential of sparse CEMRA, in particular when conventional CEMRA is too slow or does not provide sufficient spatial resolution.

References: 1. Yang CW et al. AJNR. Am. J. Neuroradiol. 2005;26:2095–101. 2. Anzalone N et al. Radiology 2005;236:204–13. 3. Nael K et al. AJNR. Am. J. Neuroradiol. 2006;27:2118–21. 4. Adcock B et al. Arxiv 2013;1302.0561. 5. Forman C et al. MAGMA 2014. 6. Liu J et al. In: ISMRM; 2012. p. 178. 7. Lustig M et al. Magn. Reson. Med. 2007;58:1182–95. 8. Wang Q et al. In: ; 2014. p. 1549. 9. Krahmer F et al. ArXiv 2012;1210.2380.

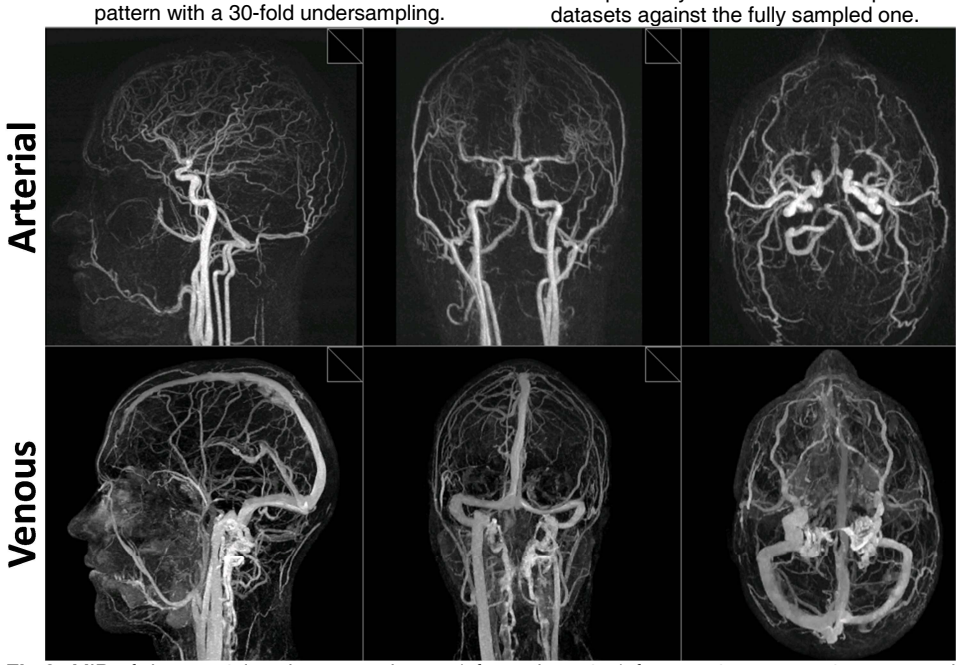

Fig.3: MIP of the arterial and venous phases (after subtraction) for a patient presenting a normal intracranial vasculature. The acquisition time per whole-head 3D volume was 10 s for a 30-fold acceleration factor.