Intracranial k-t Accelerated Dual-Venc 4D flow MRI

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TARGET AUDIENCE: This study explores the potential of measuring intracranial blood flow velocities using dual-velocity encoded 4D flow MRI. This study will most interest clinicians and clinical researchers who study or measure intracranial or liver blood flow.

PURPOSE: 4D flow MR imaging combines ECG-synchronized 3D phase-contrast MRI with advanced post-processing strategies for the in vivo assessment of 3D blood flow with full volumetric coverage of the vascular region of interest [1]. Several applications of 4D flow MRI demand the measurement of flow velocities with a high dynamic range (e.g. slow venous and fast arterial flow), e.g. intracranial aneurysms (IA) or cerebral arteriovenous malformations (AVM). However, 4D flow MRI uses fixed velocity sensitivity (*venc*), which is set above the expected maximum velocity to avoid velocity aliasing. As the velocity noise (σ_v) is directly related to the velocity sensitivity ($\sigma_v \sim venc/SNR_{mag}$), a high *venc* can substantially limit the assessment of vascular regions with low flow velocities ($v << venc$) such as small vessels or veins. We and others [2-6] have presented the application of 4D flow MRI for the in vivo evaluation of intra-aneurysmal flow and WSS in patient feasibility studies. These previous applications of 4D flow MRI were limited by its inability to fully capture the wide range of velocities inside aneurysms (high flow jet entering the aneurysm and low unstable flow, vortex and helix type flow) due to the usage of one defined *venc*. Therefore, a dual-*venc* sequence with shared reference scan and k-t acceleration for improved scan efficiency allowing the acquisition of both low- and high-*venc* data within a single scan was developed. As a result we expect to obtain 4D flow MRI data with low velocity noise across the entire velocity spectrum compared to single-*venc* implementations. The aim of this study was to apply k-t accelerated dual-*venc* 4D flow MRI for the measurement of intracranial 3D blood flow velocities to 1) enable the simultaneous acquisition of slow and fast flow and 2) improve 3D flow assessment in small intracranial vessels and veins.

METHODS: The study cohort included 7 healthy volunteers (age = 42±14, 3 females) using a 3T system (MAGNETOM Skyra, Siemens, Germany) and each subject underwent the dual-*venc* 4D flow MRI scan. The dual-*venc* sequence consisted of an ECG gated RF-spoiled gradient echo (GE) sequence with 7 subsequent TRs for dual-*venc* encoding. As illustrated in figure 1, the 1st GE was used to measure the reference k-space similarly to the standard 4D flow MRI [1]. In the following 6 TRs gradient waveforms were implemented for velocity encoding along all 3 directions with both low *venc* ($venc_I$ = 48 cm/s (4 cases) and 60 cm/s (3 cases)) and high *venc* ($venc_{II}$ = 110 cm/s (4 cases) and 130 cm/s (3 cases)) using optimized TE and TR [7]. To achieve comparable scan times as in standard 4D flow MRI, we applied *k-t* GRAPPA acceleration with R=5 and 20 x 8 ky-kz reference lines. Sequence parameters were as follows: TR/TE/FA= 6.1±0.05ms / 3.4±0.1ms / 15°, temporal/spatial resolution = 42.5±0.3ms / 1.1x1.1x1.2mm³.

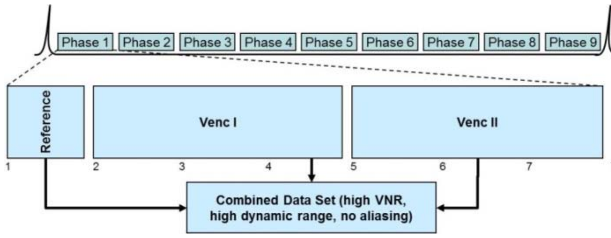

Figure 1: Dual-*venc* 4D flow MRI sequence with usage of one reference scan for both high and low *venc* velocity encoding. A combined data set for each cardiac phase was reconstructed utilizing low velocity noise of the low *venc* scan and anti-aliasing based on the high *venc* scan.

Data analysis for all 7 subjects included noise masking, velocity anti-aliasing, and corrections for Maxwell terms and eddy currents (Matlab, The Mathworks, USA) [8]. The dual-*venc* scan was combined using the eddy-current corrected but not anti-aliased low-*venc* scan and the anti-aliased high-*venc* scan. The high-*venc* scan was solely used for anti-aliasing of the low-*venc* data. Velocity noise was compared between the high-*venc* (1), low-*venc* (2) and combined (3) 4D flow data sets by calculating the standard deviation in the velocity encoded images in a static region of the brain. In addition, 3D flow visualization using 3D streamlines (Ensight, CEI, USA) of all detectable cerebral arterial and venous vessels were compared. 3D visualization quality was semi-quantitatively evaluated by an experienced Radiologist. The streamlines were emitted from the same angiogram mask and quality was graded at analysis planes (figure 2A) on a 4-point scale (0 = none of the streamlines at analysis plane, 1 = less than 50% of the streamlines at the analysis plane, 2 = more than 50%, but still incomplete, and 3 = perfect (complete)). Further regional flow quantification in all major intracranial vessels (figure 2A) was performed to quantify net flow and peak velocity (figure 2 D and E).

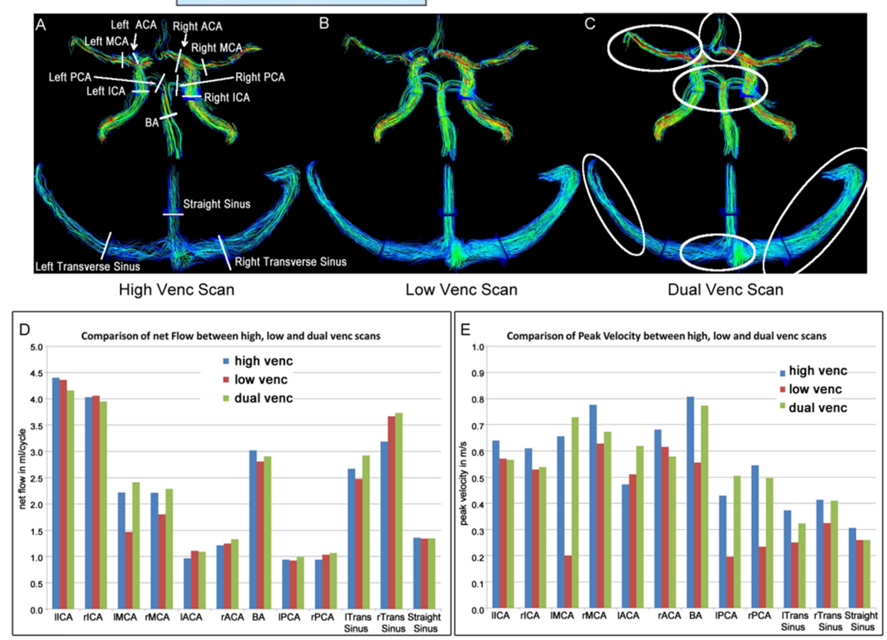

Figure 2: (A-C) example of one volunteer with 3D streamlines emitted from the entire angiogram volume for all three 4D flow scans (A high-*venc*, B low-*venc* and C dual-*venc*). In panel A the plane locations for flow qunatification are illustrated, which were used to determine net flow (D) and peak velocity (E). In panel C the areas in which dual-*venc* 4D-flow MRI provided superior flow visualization are hightlighted.

RESULTS: *k-t* accelerated dual-*venc* 4D flow MRI data was successfully acquired in all 7 subjects with an average scan time of 17±2.3 min. Pearson correlation analysis showed that peak velocities for the dual-*venc* correlated well to the high-*venc* data, but not to the low-*venc* data (R_{HV}=0.82,$P_{HV\text{-}DV}$=0.0,R_{LV}=0.06, $P_{LV\text{-}DV}$=0.3, figure 2E). Net flow for dual-*venc* 4D flow MRI showed higher correlation to the high-*venc* acquisition in arterial vessels (R_{HV}=0.96, R_{LV}=0.89, $P_{HV\text{-}DV}$=$P_{LV\text{-}DV}$=0.0), however net flow increased in venous areas and showed higher correlation to the low-*venc* acquisition (R_{LV}=0.999, R^2_{HV}=0.987,$P_{HV\text{-}DV}$=$P_{LV\text{-}DV}$=0.0, figure 2D). Velocity noise in high-*venc* data was 0.0036 ± 0.0011 m/s (range=0.0023-0.0053 m/s) compared to 0.0019 ± 0.00075 m/s (range=0.001 – 0.0032 m/s) for dual-*venc* 4D flow MRI corresponding to a 42% noise reduction. Quality grading for high- /low- /dual-*venc* scans (1.7 vs. 1.8 vs 2.0, $P_{LV\text{-}DV}$=0.05, $P_{HV\text{-}DV}$>0.001) revealed improvement of 3D flow visualization for dual-*venc* 4D flow MRI data (less aliasing in arteries, improved depiction of venous 3D flow patterns).

DISCUSSION AND OUTLOOK: The findings of this feasibility study show that *k-t* GRAPPA accelerated dual-*venc* 4D flow MRI can provide improved visualization and quantification of venous and arterial hemodynamics across a wide range of the velocity spectrum. Velocity noise was significantly reduced compared to the standard single-*venc* implementations. In the future, optimized dual-*venc* 4D flow MRI can be applied for improved in-vivo measurement of intracranial arterial malformation or aneurysm hemodynamics.

REFERENCES: [1] Markl M et al, JMRI 2007; [2] Hope et al, MRI 2010; [3] Rayz et al, Annals of biomedical engineering 2010; [4] Boussel et al, MRM 2009;; [5 Meckel et al, Neuroradiology 2008; [6] Kecskemeti S et al, JMRI 2011; [7] Bernstein MA et al, JMRI 1992; [8] Bock et al. ISMRM 2007, abstract 3138

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