Diffusion Tensor MRI of the Entire Human Heart *in Vivo* with Blipped-CAIPI and Simultaneous Multislice Acquisition

Choukri Mekkaoui[1], Timothy G Reese[2], Himanshu Bhat[3], Stephen T Cauley[2], Marcel P Jackowski[4], Kawin Setsompop[2], and David E Sosnovik[5]

[1]*Harvard Medical School - Massachusetts General Hospital, Boston, MA, United States,* [2]*Athinoula A Martinos center for Biomedical imaging, Boston, United States,* [3]*Siemens, boston, United States,* [4]*University of São Paulo, São Paulo, Brazil,* [5]*Harvard Medical School - Massachusetts General Hospital, Boston, United States*

Target Audience: Scientists/clinicians interested in MRI of the heart.

Purpose: In vivo Diffusion Tensor MRI (DTI) of the heart provides highly valuable information but is extremely time consuming. Each 2D slice requires a minimum of 14 heartbeats to acquire and, in addition, up to 8 averages are needed for optimal measurement of the diffusion eigensystem. Most implementations of in vivo cardiac DTI have thus so far sampled only 3-5 short axis slices with large interslice gaps. Here we aimed to use blipped-CAIPI, a recently-developed slice acceleration technique[1], to simultaneously image multiple 2D slices in each breath-hold. This, we hypothesized, would decrease the acquisition time needed for cardiac DTI by a factor of 3 and allow the entire human heart to be imaged in vivo with high resolution and without interslice gaps.

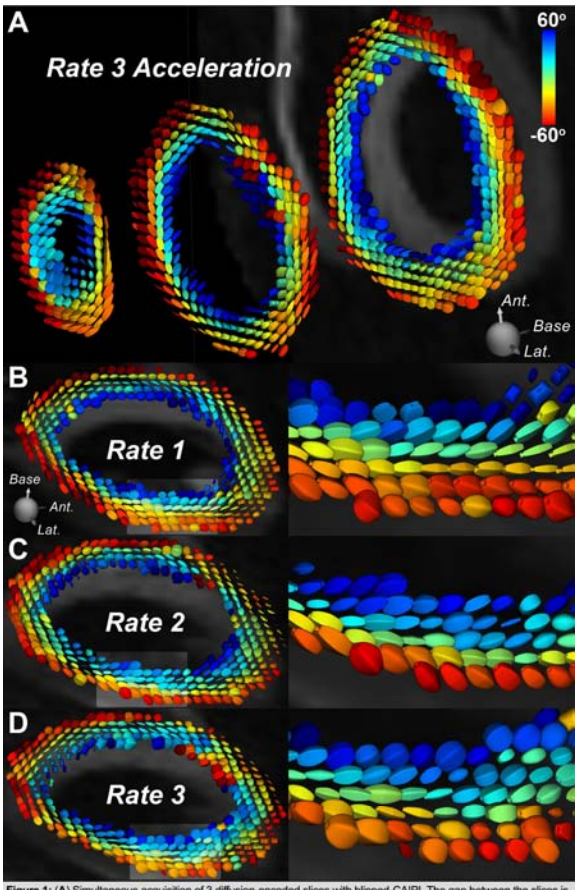
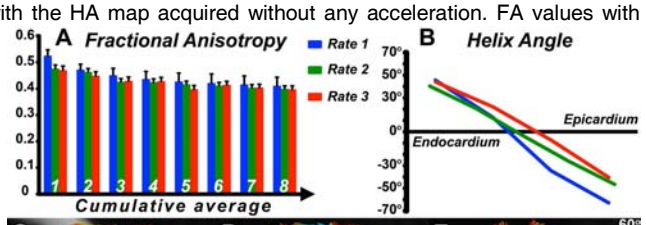


Figure 1: (**A**) Simultaneous acquisition of 3 diffusion-encoded slices with blipped-CAIPI. The gap between the slices is 500% of slice thickness. After 8 averages, the slice group is shifted 8mm apically. The eigensystem in each slice is represented by supertoroid glyphs, color coded, and oriented by helix angle (HA). (**B-D**) Supertoroidal glyph field at the same location in the left ventricle acquired with no slice acceleration (**B**), rate 2 blipped-CAIPI (**C**), and rate 3 blipped-CAIPI (**D**). The data acquired with slice acceleration correlate well with the unaccelerated slice and the transmural evolution of HA from the endocardium to the epicardium can be well resolved.

Methods: Normal volunteers were imaged on a 3T scanner (Skyra PTx, Siemens Healthcare) using a single transmit channel and a 34 element thoracic array. DTI was performed with a diffusion encoded stimulated echo sequence[2], enhanced with volume selection in the phase-encode axis. Image parameters included: FOV 400x200mm, resolution 2.7x2.7x8mm^3, in-plane GRAPPA rate 2, TE=37ms, b-value=500 s/mm^2, 10 diffusion encoding directions. 18 short axis slices were acquired in the systolic sweet spot of the cardiac cycle to mitigate strain effects[3]. Imaging was performed with no slice acceleration, rate 2 and rate 3 slice acceleration. With rate 2 and rate 3 slice acceleration, the simultaneously acquired 2D slices were separated by 700% and 500% of slice thickness, respectively. Eight averages (breath-holds) were acquired at each location, after which the slice/slice group was shifted by 8mm. The images were segmented using the standard 16-segment AHA model and parameters including fractional anisotropy (FA) and the transmural slope in helix angle (HA) were calculated as previously described[4], and compared with repeated measures ANOVA. Fiber tracts were constructed by integrating the primary eigenvector field into streamlines using an adaptive 5th order Runge-Kutta approach and color coded by HA.

Results: Without blipped-CAIPI, the acquisition of 13 short axis slices required 2 hours. With blipped-CAIPI, 18 short axis slices were acquired in < 1 hour with rate 2 acceleration and in < 40 minutes with rate 3 acceleration. Image quality was well preserved in both the rate 2 and rate 3 blipped-CAIPI acquisitions. This is demonstrated in Fig 1A, where a set of three simultaneously imaged slices (rate 3) is shown. In each slice, the eigensystem is depicted with supertoroid glyphs, oriented and color-coded by HA. The transmural evolution in HA from positive in the subendocardium to negative in the subepicardium is well resolved in all 3 slices. Supertoroid fields at the same short axis location in the left ventricle in one of the volunteers are shown with no acceleration (Fig. 1B), rate 2 acceleration (Fig. 1C), and rate 3 acceleration (Fig. 1D). The rate 2 and 3 maps compare extremely favorably with the HA map acquired without any acceleration. FA values with and without acceleration were similar and in all three cases required at least 5 signal averages to converge (Fig 2A). HA required 8 signal averages to converge in both the unaccelerated and accelerated datasets and showed a similar transmural profile in the datasets acquired with and without blipped-CAIPI (Fig. 2B). High quality tractography of the entire heart could be performed with the rate 1 as well as the rate 2 and rate 3 slice-accelerated datasets (Fig. 2C).



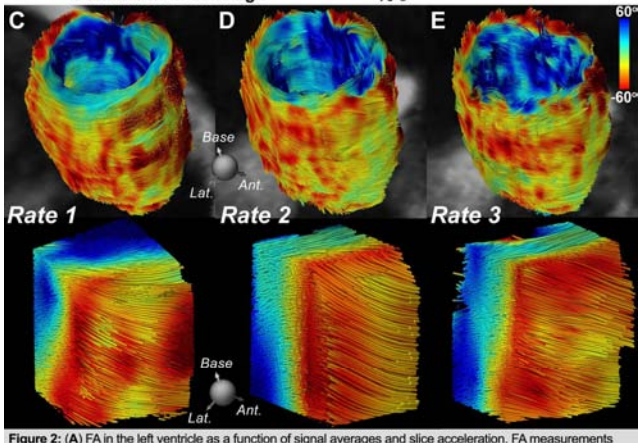


Figure 2: (**A**) FA in the left ventricle as a function of signal averages and slice acceleration. FA measurements converge, for all slice acceleration factors, with >4 signal averages. HA values, even without slice acceleration, converge with >7 breath-holds and 8 averages per slice were thus acquired. (**B**) Transmural plots of HA with and without blipped-CAIPI are similar. (**C-E**) Tractography of the LV, color coded by HA, in the same volunteer imaged with no slice acceleration (**C**), rate 2 blipped-CAIPI (**D**) and rate 3 blipped-CAIPI (**E**). Magnified views of tracts in a small ROI in the lateral wall are shown below the images of the entire heart. Image quality with rate 2 and 3 blipped-CAIPI is high and a strong concordance is seen between the tracts acquired with and without slice acceleration.

Discussion: The utilization of cardiac DTI has been limited in part by its temporal inefficiency. Here we show that simultaneous multislice acquisition using the blipped-CAIPI technique can be used to increase coverage and reduce scan time by a factor of 3. In vivo DTI of the entire human heart can be performed with this technique in 40 minutes with acceptable resolution, without interslice gaps, and with excellent image quality. The improved coverage and reduced scan time produced by blipped-CAIPI have the potential to improve the accuracy of cardiac DTI and facilitate its clinical use.

Conclusion: Cardiac DTI with simultaneous multislice acquisition is possible and reduces scan time by 3-fold without a loss of image quality. Blipped-CAIPI may be of value with other long echo train 2D sequences in the heart as well.

References: 1) Setsompop K *et al.* MRM 2012. 2) Reese TG *et al.* 1995. 3) Dou J *et al.* MRM 2002. 4) Mekkaoui C *et al.* ISMRM 2011.