Free-Breathing Diffusion Tensor MRI of the Entire Human Heart In Vivo Using Simultaneous Multislice Excitation and Spatiotemporal Registration

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Target Audience: Scientists/clinicians interested in MRI of the Heart and Diffusion Tensor MRI (DTI).

Purpose: Diffusion Tensor Imaging (DTI) of the heart *in vivo* has largely been performed using multiple breath-holds. The clinical translation of cardiac DTI, however, will require efficient free-breathing techniques to be developed. The use of diaphragmatic navigators to facilitate free-breathing DTI of the heart was recently described[1], however, the acquisition of only 3 short-axis slices in this study took approximately 20 minutes. We have recently implemented the blipped-CAIPI approach to simultaneously excite multiple slices during a DTI acquisition.[2] We hypothesized that i) the integrated use of a NAV with SMS excitation would increase the efficiency of whole-heart cardiac DTI and ii) that this could be accomplished without a penalty in image quality through the use of advanced spatiotemporal registration (STR) techniques.[3] Here we aimed to combine simultaneous multislice (SMS) excitation and a diaphragmatic navigator (NAV) to perform free-breathing DTI of the entire human heart *in vivo*, without slice gaps, in under 25 minutes.

Methods: DTI was performed in 7 healthy volunteers on a clinical 3T scanner (Skyra, Siemens) using a fat-suppressed, zone-selected, diffusion-encoded stimulated echo (STE) sequence with 10 diffusion encoding directions, TE/TR 36 ms/2 R-R intervals, GRAPPA rate 2, b-value 500 s/mm^2, resolution 2.5x2.5x8 mm^3, and 8 averages, using both the multiple breath-hold and free-breathing (NAV) approaches. The entire left and right ventricles were covered in 12 contiguous short-axis slices without gaps. Rate 3 SMS with the blipped-CAIPI approach was used in both the breath-hold and free-breathing acquisitions. In addition, breath-hold data were acquired using rate 1 SMS (conventional single slice). A NAV with a 4-mm acceptance range was placed both before and after the STE readout. Images were acquired in the systolic sweet spot of the cardiac cycle[4] and were co-registered using STR.[3] Tractography was performed by numerically integrating the primary eigenvector field into streamlines using an adaptive 5th order Runge-Kutta approach. The impact of SMS on myofiber helix angle (HA), mean diffusivity (MD), and fractional anisotropy (FA) was evaluated in the same short axis slice at the mid-ventricular level using the rate 1 and 3 SMS acquisitions (n=7 in each group) and compared with nonparametric statistics (Komolgorov-Smirnov test).

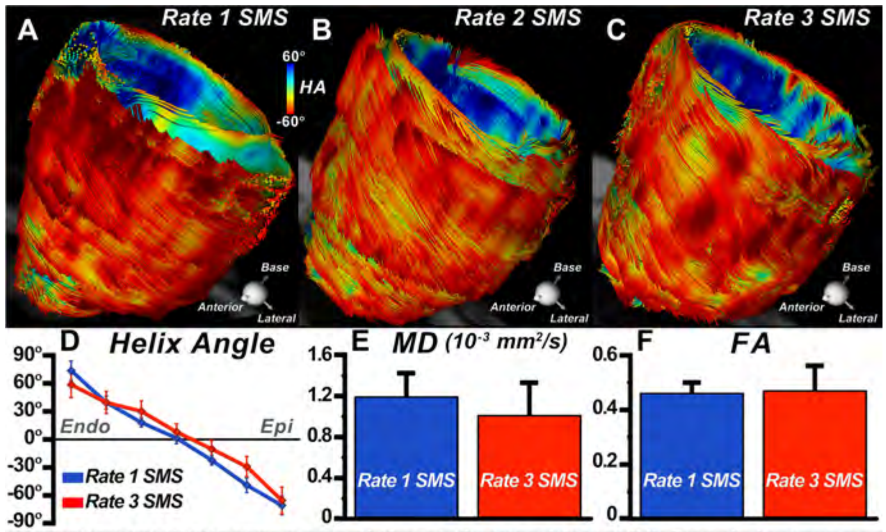

Figure 1: Breath-hold DTI of the same volunteer with (**A**) rate 1, (**B**) rate 2, and (**C**) rate 3 SMS. The resolved tracts are color-coded by HA. Tract coherence remains high with both rate 2 and rate 3 SMS. No significant differences were seen between the rate 1 and rate 3 acquisitions (n=7) in (**D**) the transmural slope of HA, (**E**) MD, and (F) FA.

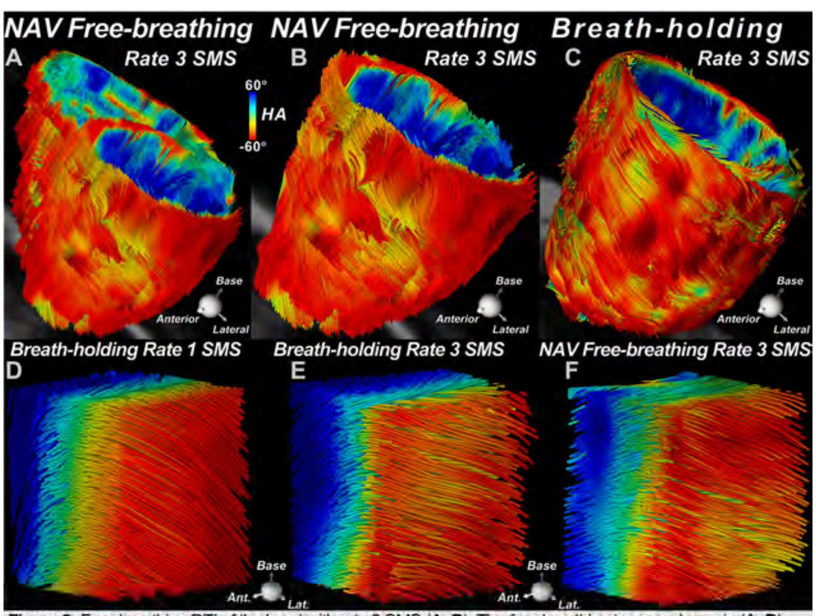

Figure 2: Free-breathing DTI of the heart with rate 3 SMS (**A**, **B**). The free-breathing images shown in (**A**, **B**) were acquired with 6 signal averages in under 25 minutes and compare favorably with a rate 3 SMS breath-hold scan (**C**), which was acquired with 8 averages. The characteristic evolution of myofiber HA is well resolved with a rate 1 breath-hold scan (**D**), rate 3 SMS breath-hold scan (**E**), and a SMS free-breathing NAV scan (**F**).

Results: DTI of the entire heart could be successfully performed with the blipped-CAIPI SMS approach with minimal loss of image quality. This is shown in Figure 1A-C, where the same volunteer was imaged with rate 1, 2, and 3 SMS. The coherence of the resolved tracts in the rate 3 SMS acquisition compares favorably with the rate 1 study, despite requiring only 1/3 of the acquisition time. No significant differences were seen in MD, FA, or the transmural slope of HA between the rate 1 and rate 3 SMS acquisitions (Figure 1D-F). The quality of the tracts produced by the rate 3 SMS NAV scans was high (Figure 2A-B) and very similar to that of the breath-hold rate 3 SMS scans (Figure 2C). This is shown in detail in a magnified view of a region-of-interest in the lateral wall (Figure 2D-F). Reducing the number of averages in the navigator scan from 8 to 6 allowed the entire heart to be imaged in under 25 minutes while still maintaining excellent image quality (Figure 2A,B,E).

Discussion: DTI of the heart can be accurately performed using a NAV-based blipped-CAIPI STE sequence with rate 3 SMS excitation and STR. This enables the entire heart to be imaged in under 25 minutes without compromising image quality. The elimination of breath-holds in favor of a free-breathing NAV approach makes whole-heart DTI tractography accessible to patients with a broad range of cardiovascular conditions.

Conclusion: The combination of SMS excitation, a NAV-based free-breathing approach, and STR enables DTI with full cardiac coverage and reduced scan time. This has significant implications for the clinical translation of cardiac DTI.

References: 1) Nielles-Vallespin S, et al., MRM 2013; 2) Setsompop, et al., MRM 2012; 3) Mekkaoui, et al., JCMR 2013; 4)Tseng WY, et al., MRM 1999.