# Free-breathing cardiac DTI with simultaneous multi-slice excitation

Constantin von Deuster[1,2], Christian T. Stoeck[2], Martin Buehrer[2], Jack Harmer[1], Rachel W. Chan[3], David Atkinson[3], and Sebastian Kozerke[1,2]

[1]*Division of Imaging Sciences & Biomedical Engineering, King's College London, London, London, United Kingdom,* [2]*Institute for Biomedical Engineering University and ETH Zurich, University and ETH Zurich, Zurich, Zurich, Switzerland,* [3]*Centre for Medical Imaging, University College London, London, London, United Kingdom*

**Introduction:** Diffusion weighted and diffusion tensor imaging of the in-vivo human heart using the Stimulated Echo Acquisition Mode (STEAM) was successfully demonstrated almost twenty years ago[1,2] . To reduce strain effects by cardiac motion, the use of strain correction[2], careful timing of diffusion encoding to the "sweet spots" in the cardiac cycle[3] and velocity compensated diffusion gradient waveforms[4] have been proposed. Robust signal averaging in STEAM requires exact geometrical alignment of the heart in successive heartbeats. However, acquiring consistent breathholds is challenging in practice. In more recent implementations, cardiac STEAM diffusion imaging was combined with respiratory navigation and biofeedback allowing for data collection during guided free breathing of the subject[5]. However, given the strict respiratory gating conditions for STEAM, total scan times remain long, making it very difficult to acquire data from a number of slices as required for 3D tensor reconstructions[6]. The objective of the present work is to propose a navigated, simultaneous slice excitation implementation for free-breathing cardiac diffusion imaging using STEAM. By using an improved navigator gating strategy and dual-slice excitation, significant improvements in scan efficiency are demonstrated relative to previous free-breathing approaches[5].

**Methods:** Cardiac diffusion tensor imaging using STEAM was implemented on a 1.5T Philips Achieva system (Philips Healthcare, Best, The Netherlands) equipped with a 32-channel cardiac receiver array. Fat suppression was achieved by frequency-selective saturation prior to the first 90° excitation. For each diffusion-encoding direction, eight averages were acquired. Imaging parameters were as follows: resolution 2.5×2.5mm$^2$, slice thickness 8mm, FOV: 200×100mm$^2$, TE 15ms, TR: 2-R-R intervals, partial Fourier sampling (65%). Unipolar Stejskal-Tanner gradients with a b-value of 400s/mm$^2$ were played out in ten directions[7] and timed to the strain "sweet spots"[3]. Inner volume excitation ("local look") was used to reduce the field-of-view in phase encode direction. Data were acquired in three healthy subjects upon obtaining written informed consent according to institutional guidelines.

*Navigator gating:* To improve the navigator gating efficiency, the gating strategy was modified to repeat STEAM encoding block until the respiratory level as measured with a pencil beam navigator (NAV1, Figure 1) was within a 5mm gating window centered at the end-expiratory level. If the breathing position exceeded the 5mm navigator window, a 90° block pulse was applied to guarantee similar excitation history as if data was accepted. Upon acceptance of the end-expiratory position, the 90° block pulse was replaced on the fly by the inner volume/dual-slice pulses (Figure 1). STEAM encoding was then followed by the STEAM decoding block including data acquisition. Sampled data were accepted if the relative displacement between NAV1 and NAV2 was within +/- 0.5mm.

*Dual-slice excitation*: The 90° RF pulses for dual slice excitation were designed using the Shinnar-Le Roux algorithm[8], producing two passbands of 8mm thickness and a stopband corresponding to a slice gap of 32mm. Blipped CAIPIRINHA[9,10] was implemented to generate a phase difference of π between both slices for every second k-space line. Images were reconstructed by inverting the forward model:

$$\begin{pmatrix} I_1 \\ \vdots \\ I_{32} \end{pmatrix} = \begin{pmatrix} C_{1.1} & C_{1.2} \\ \vdots & \vdots \\ C_{32.1} & C_{32.2} \end{pmatrix} \cdot \begin{pmatrix} M_1 \\ M_2 \end{pmatrix}$$

where *C* denotes coil sensitivity and *M* the desired unaliased image voxels. The coil sensitivity matrix *C* was determined using a separate reference scan acquired within two additional breath holds. Image reconstruction was performed using the ReconFrame framework (GyroTools LLC, Zurich, Switzerland). Prior to tensor calculus, the diffusion weighted scans were additionally registered to the b=0s/mm$^2$ image to account for any residual displacements. For reference, conventional single-slice cardiac diffusion data were acquired within 22 breathholds.

**Results:** Figure 2 shows diffusion tensor maps at mid-ventricular slice and apical level reconstructed from free-breathing, dual-slice imaging relative to conventional single-slice breathheld acquisitions. Navigator gating efficiency of the navigated, duals-slice approach was measured to be 35.4 +/- 4.7% which demonstrates a significant improvement in scan efficiency compared to previous studies with gating efficiencies of 20.9 +/- 4.8% [5]. Furthermore, effective scan efficiency was doubled, as two slices were acquired concurrently, resulting in average scan times per slice of 2.8 +/- 0.4 min. The helix angle, i.e. the diffusion tensor's first eigenvector relative to the transmural plane, as a function of transmural depth for both slices is shown in Figure 3. The deviation of helix angles between the navigated CAIPIRINHA method and the breathhold reference scan for slice 1 and 2 were: 3.4 +/-2 deg and 4.0 +/- 3.0 deg, respectively.

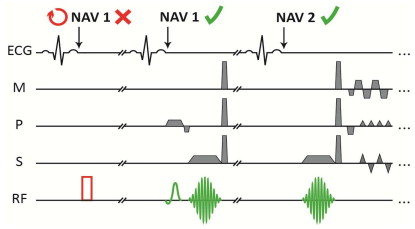


*Fig. 1: Free breathing cardiac DTI sequence with additional 1D navigators, CAIPIRINHA blips and dual-band RF pulses. NAV 1 is repeated until acceptance, followed by NAV 2.*

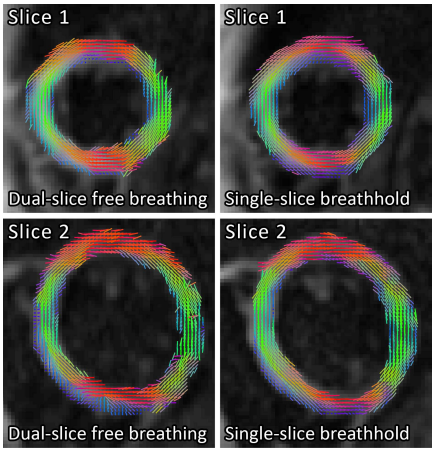


*Fig. 2: Diffusion tensors images acquired by the proposed free breathing CAIPI method (left) and single-slice breathhold reference (right).*

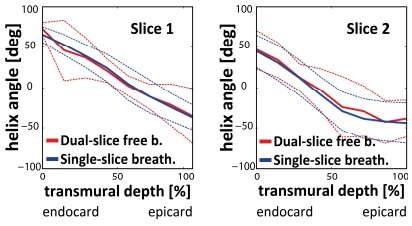


*Fig. 3: Helix angles derived from dual-slice free-breathing vs. single-slice sequential acquisitions (solid: mean angle, dashed: one standard deviation across the volume of interest).*

**Discussion:** In this work, a free breathing navigated dual-slice STEAM method was successfully implemented yielding an approximately 3.5-fold increase in scan efficiency as compared to previous approaches[5]. Successful reconstruction requires a variation in coil sensitivites, hence dedicated cardiac coil arrays are necessary. Furthermore $B_0$ homogeneity needs to be guaranteed over a larger volume as compared to single slice acquisition.

**References:** 1. Edelman MRM 1994; 2. Reese MRM 1995 ; 3. Tseng et al. MRM 1999; 4. Dou et al. MRM 2002 5. Nielles-Vallespin et al. MRM 2013 ; 6. Toussaint et al. MICCAI 2010; 7. Jones et al. MRM 1999; 8. Pauly et al. IEEE TMI 1991; 9. Breuer et al. MRM 2005; 10. Setsompop et al. MRM 2012

**Acknowledgements:** This work is supported by UK EPSRC.