Cardiac Diffusion Tensor MRI Using Simultaneous Multi-Slice Acquisition with a Blipped-CAIPIRINHA Readout

Choukri Mekkaoui[1]; Timothy G. Reese[1]; Marcel P. Jackowski[2]; Himanshu Bhat[3]; David E. Sosnovik[1,4]

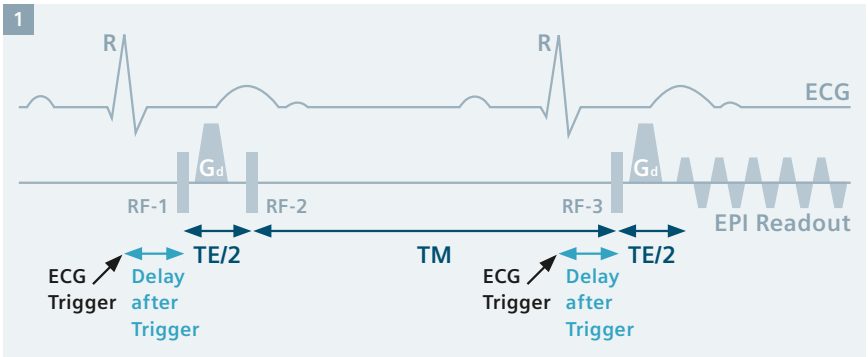
[1] Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA
[2] Department of Computer Science, Institute of Mathematics and Statistics, University of São Paulo, São Paulo, Brazil
[3] Siemens Healthcare, Charlestown, MA, USA
[4] Cardiovascular Research Center, Cardiology Division, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA

Background

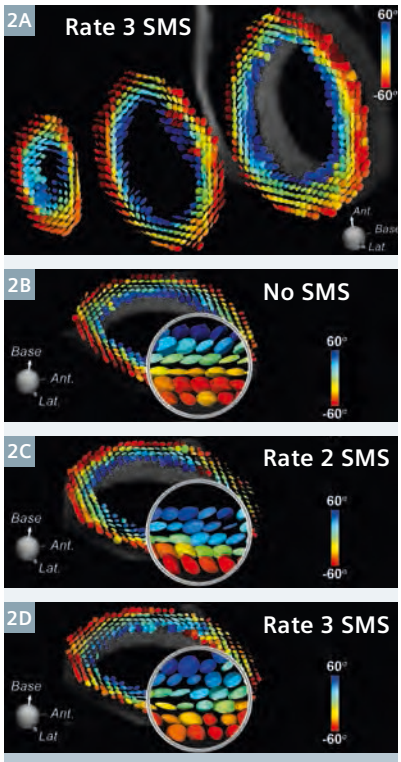
Heart muscle is highly anisotropic with an intricate microstructure, well suited to characterization with diffusion tensor imaging (DTI) [1]. The most widely used measure of fiber organization in the myocardium is the helix angle (HA), simply defined as the inclination of the myofiber out of the local short-axis plane. Myofibers in the subendocardium have a positive HA, while those in the subepicardium have a negative HA [1, 2]. These myofibers are further arranged into laminar sheets, which slide against each other allowing the myocardium to thicken during systole [3, 4]. Alterations of this microstructure due to heart disease affect its mechanical efficiency and also could contribute to arrhythmias [5, 6]. These microstructural changes can precede symptoms and thus a non-invasive evaluation could be of significant clinical value.

The motion of the heart is five orders of magnitude greater than the self-diffusion of water. Therefore, approaches that are sensitive to the microscopic diffusion of water, but not to cardiac motion and strain, are needed for successful *in vivo* imaging [7-9]. One approach to enable *in vivo* DTI uses a diffusion-encoded stimulated echo (STE) sequence (Fig. 1), which can be implemented on most clinical scanners [10, 11]. The diffusion-encoded STE sequence is played out over two successive heartbeats. The first and second 90° excitation pulses are applied in the first heartbeat, and the third excitation pulse in the second heartbeat. The diffusion-encoding gradients are monopolar and placed immediately after the first and third excitation pulses. The main appeal of the STE approach is its conceptual immunity to cardiac motion. Ideally, each monopolar diffusion gradient occurs at exactly the same time in two sequential R-R intervals. Hence, not only is the phase due to the diffusion-encoding gradient unwound, but the influence of cardiac motion on the phase of the magnetization also is unwound.

The use of a STE sequence, however, introduces a high degree of inefficiency into the acquisition due to the dual-gated acquisition. Additionally, the STE is half the amplitude of a spin-echo. Consequently most investigators have used ~8 averages per slice in order to achieve sufficient signal-to-noise (SNR) during diffusion-encoded STE acquisitions, taking 5-7 minutes per slice [12]. The inefficiency of the STE approach frequently requires the anatomical coverage of the acquisition to be compromised. For instance, only 3 short-axis slices can be imaged in ~15 minutes, which covers only 25% of the myocardium [12]. New approaches to improve anatomical coverage and reduce scan time are thus sorely needed. The development of simultaneous multi-slice (SMS) acquisition using a blipped Controlled Aliasing in Parallel Imaging (blipped-CAIPIRINHA) readout holds great promise [13, 14], and could play a key role in facilitating the more widespread use of cardiac DTI.



1 Dual gated stimulated echo (STE) sequence. Three 90° excitation pulses (RF) are applied over two successive heartbeats. The excitation (RF-1), refocusing (RF-3), and diffusion dephase and rephrase occur at the same time in the R-R intervals, thereby exploiting periodicity of heart motion to rewind motion related dephasing. Additionally, the long diffusion time (including TM), allows a sufficient b-value to be produced on clinical scanners without the need for an excessively long TE.



2 **(2A)** Simultaneous acquisition of 3 slices with rate 3 SMS. The gap between the slices is 500% of slice thickness. The tensor field is represented by supertoroids color-coded by HA. Supertoroid fields resulting from no SMS **(2B)**, rate 2 **(2C)**, and rate 3 **(2D)** SMS acquisitions of the same mid-ventricular slice are consistent with the transmural change in HA from positive in the subendocardium to negative in the subepicardium.

Implementation

The technical details of SMS excitation using blipped-CAIPIRINHA have been described in detail elsewhere in this volume. The technique has been used extensively in the brain [13, 14], and preliminary experience with it in the heart appears promising [15]. In the current article, we describe our experience with this technique for cardiac DTI in healthy volunteers.

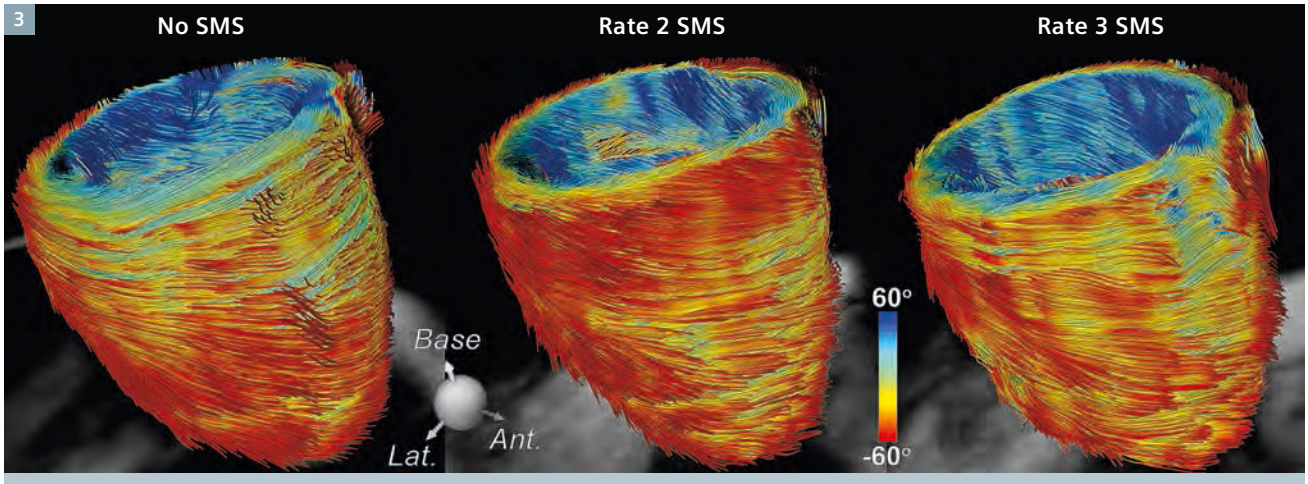
Breath-hold DTI was performed on a clinical 3T scanner (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany) with a 34-element receive coil[1] (18 anterior and 16 posterior elements). Images were acquired with a diffusion-encoded STE sequence, which was volume-selected in the phase-encode axis using a slab selective radiofrequency (RF) pulse. Acquisition parameters included: FOV 360 x 180 mm, resolution 2.5 x 2.5 x 8 mm^3, in-plane GRAPPA rate 2, TE 34 ms, b-value 500 s/mm^2, 10 diffusion-encoding directions, and 8 averages. Twelve short-axis slices were acquired in the systolic sweet spot of the cardiac cycle to mitigate strain effects [11, 16]. Imaging was performed with no SMS, and rates 2 and 3 SMS. HA was derived from the diffusion tensor, which was estimated from the diffusion-weighted images. Fiber tracts were constructed by integrating the primary eigenvector field into streamlines using an adaptive 5th order Runge-Kutta approach [5].

Results and impact

With no SMS, 96 breath-holds were required to cover the entire LV. Using rate 2 SMS, this was reduced to 48 breath-holds, and with rate 3 SMS to 32. With rate 3 SMS, the acquisition time was approximately 20 minutes for whole-heart coverage. Image quality was well preserved using both rates 2 and 3 SMS. This is demonstrated in Figure 2, where the diffusion tensor in each voxel is represented by the supertoroidal model [17]. The glyphs are parameterized by the magnitude and orientation derived from the diffusion tensor 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 with rate 3 SMS. Glyph fields using rates 2 and 3 SMS of a mid-ventricular slice compare favorably with those acquired with no SMS, and are consistent with expected transmural evolution in HA.

Tractography of the heart has previously been performed over a small anatomical range (3-5 slices) or with very large slice gaps. Meaningful tractography requires the entire heart to be imaged without any slice gaps.

[1] The product is still under development and not commercially available yet. Its future availability cannot be ensured.



3 Tractography of the entire LV, color-coded by HA, of the same subject imaged with no SMS, and rates 2 and 3 SMS. Tracts obtained using rates 2 and 3 SMS compare favorably and are in agreement with those obtained with no SMS.

With no SMS, this takes over 60 minutes to acquire. However, as shown in Figure 3, fiber tracts of the entire LV were successfully obtained with rates 2 and 3 SMS, and are qualitatively comparable with those obtained with no SMS.

Discussion

DTI of the heart has the potential to improve the understanding, diagnosis and management of a range of cardiovascular diseases. However, the main limitation is long scan times. With current techniques, the acquisition of 3 short-axis slices takes ~20 minutes. We demonstrated that using SMS, scan time was reduced by 3-fold. The simultaneous acquisition of 3 slices (basal, medial, and apical), as shown in Figure 2, takes ~5 minutes. While imaging only 3 slices yields limited coverage of the LV, the utility of this approach has been demonstrated in first-pass perfusion studies of the heart [18]. The additional acquisition of DTI images in the same 3 short-axis slices would add little time to a clinical study and could be of substantial value.

DTI of the entire heart, while more demanding, could provide a unique way to evaluate myocardial microstructure. SMS combined with further technical advances may facilitate the clinical translation of whole-heart DTI, enabling the reliable characterization of myocardial structure in a wide range of patients with cardiac diseases.

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Timothy G. Reese

Choukri Mekkaoui

Contact

Choukri Mekkaoui
Athinoula A. Martinos Center for Biomedical Imaging
149 13th Street
Charlestown, MA 02129, USA
Phone: +1 617 724-3407
Fax: 617 726-7422
mekkaoui@nmr.mgh.harvard.edu