Accelerated Diffusion Tensor Imaging of Skeletal Muscle Using Simultaneous Multi-Slice Acquisition

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Abstract

Simultaneous multi-slice acquisition with CAIPIRINHA reduces the scan time in diffusion-weighted magnetic resonance imaging. In this article, we resume our early experience with this technique for accelerated diffusion tensor imaging of skeletal muscle [1].

Introduction

Diffusion tensor imaging (DTI) is based on measuring the diffusion of water molecules along six or more gradient directions. In contrast to conventional diffusion-weighted imaging, DTI provides voxel-wise information not only on the amount (mean diffusivity, MD) but also on the anisotropy (fractional anisotropy, FA) and direction of diffusion.
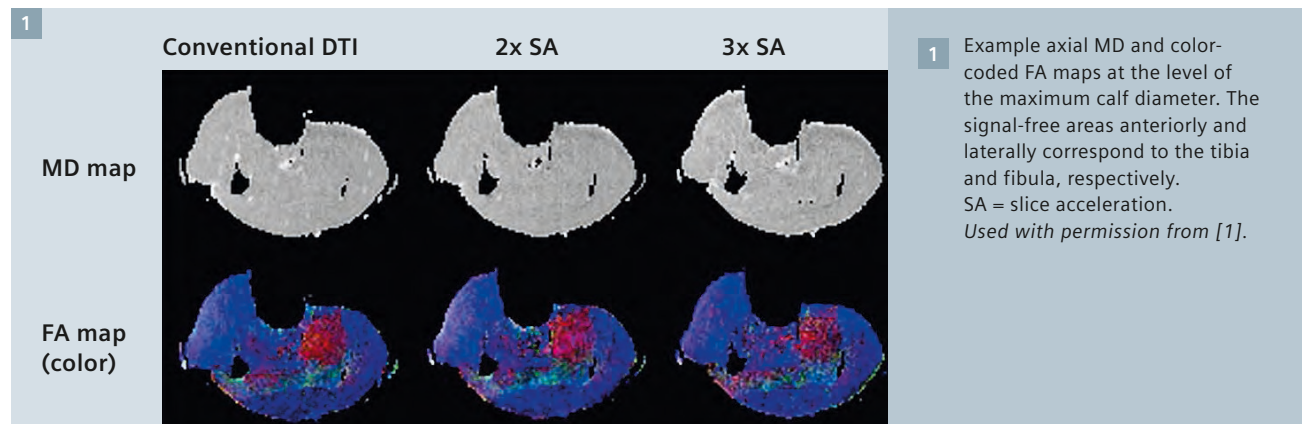
In previous studies, DTI was used for characterizing the fiber course and physiological muscle behavior as well as pathological changes such as muscle tears or edema [2-7]. Theoretically, skeletal muscle has an ideal tissue structure for DTI applications given its long, parallel fibers. However, the relatively short T2 relaxation time in muscle leads to an inherently unfavorable signal-to-noise ratio (SNR), which needs to be compensated by the acquisition of multiple signal averages. Thus, the clinical applicability of muscle DTI is currently limited by its long scan time.

A promising new approach to overcome this limitation is simultaneous multi-slice acquisition with blipped-CAIPIRINHA [8-10]. In brief, this technique excites multiple slices at once and applies phase shifts during readout. The reconstruction uses the spatial sensitivity of coil elements to separate the signal contributions from the different slices. We used this technique for accelerated DTI of the calf muscles and hypothesized that similar image quality could be achieved compared to standard DTI.

Methods

We scanned the calf of eight healthy subjects (age, 29.4 ± 2.9 years) in a 3T scanner (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany) with a dedicated 15-channel knee coil. DTI was performed by applying 20 different diffusion encoding directions at a b-value of 500 s/mm^2. In addition to a conventional DTI sequence, simultaneous multi-slice acquisition was performed with a dedicated work-in-
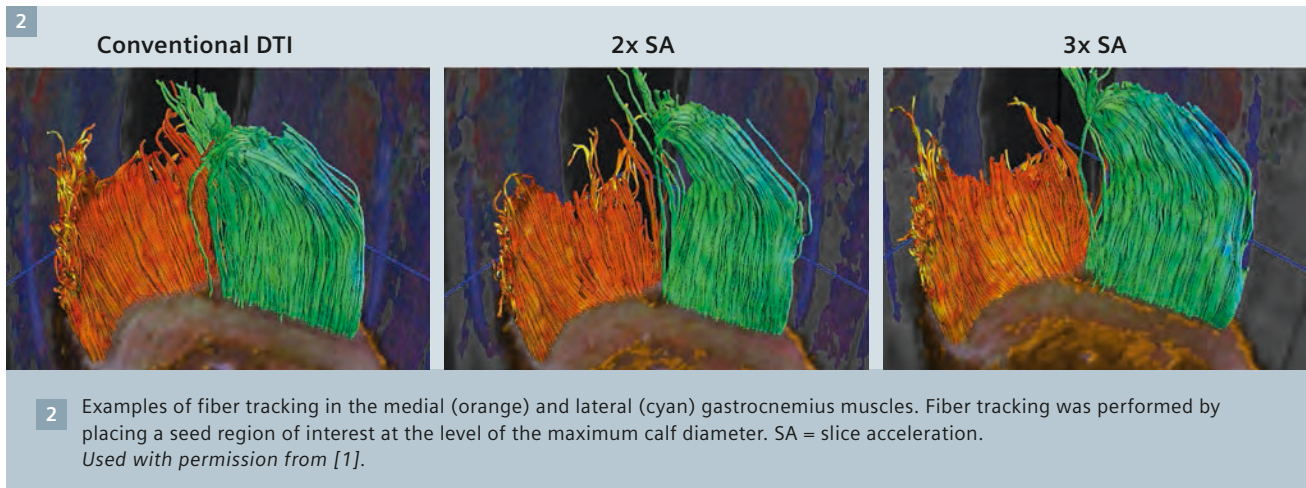

1

	Conventional DTI	2x SA	3x SA
MD map			
FA map (color)			

1 Example axial MD and color-coded FA maps at the level of the maximum calf diameter. The signal-free areas anteriorly and laterally correspond to the tibia and fibula, respectively. SA = slice acceleration. *Used with permission from [1].*

2

| Conventional DTI | 2x SA | 3x SA |

2 Examples of fiber tracking in the medial (orange) and lateral (cyan) gastrocnemius muscles. Fiber tracking was performed by placing a seed region of interest at the level of the maximum calf diameter. SA = slice acceleration.
Used with permission from [1].

Table 1:

	Conventional DTI		Slice acceleration factor 2		Slice acceleration factor 3	
	MD (10⁻³ mm²/s)	FA	MD (10⁻³ mm²/s)	FA	MD (10⁻³ mm²/s)	FA
Medial gastrocnemius	1.62 ± 0.09	0.22 ± 0.01	1.60 ± 0.04	0.23 ± 0.02	1.61 ± 0.12	0.24 ± 0.02
Lateral gastrocnemius	1.68 ± 0.06	0.22 ± 0.02	1.64 ± 0.10	0.23 ± 0.02	1.68 ± 0.10	0.24 ± 0.02
Soleus	1.67 ± 0.10	0.24 ± 0.03	1.64 ± 0.08	0.23 ± 0.02	1.65 ± 0.09	0.27 ± 0.04
Tibialis anterior	1.74 ± 0.10	0.35 ± 0.05	1.71 ± 0.14	0.36 ± 0.05	1.83 ± 0.10	0.38 ± 0.06

Fractional anisotropy (FA) and mean diffusivity (MD) measured in the calf muscles. *Used with permission from [1].*

progress package[1] running on the *syngo* MR D13C platform. Two different protocols were acquired with a slice acceleration factor of two and three slices, respectively.

In all sequences, we measured MD and FA values in the medial and lateral gastrocnemius, soleus, and tibialis anterior muscles. In addition, DTI fiber tracking was performed with dedicated post-processing software ('Neuro 3D' application, *syngo* MMWP, Siemens Healthcare, Erlangen, Germany). The success of fiber tracking was compared between the standard and slice-accelerated DTI sequences both quantitatively (number of tracks, average track length) and qualitatively (anatomical precision score, ranging from 1 = poor to 5 = excellent). Last, the SNR was estimated for all sequences by using the subtraction method [11, 12].

Results

Compared to the conventional DTI sequence (7:24 min), significantly shorter acquisition times could be achieved with slice acceleration factor 2 (3:53 min) and 3 (2:38 min).

MD values were similar in all sequences ($p \geq 0.20$). FA values were similar in conventional DTI and two-fold slice acceleration but higher with three-fold slice acceleration ($p = 0.006$) (Table 1).

Fiber tracking worked equally well with conventional DTI and two-fold slice acceleration. However, with three-fold slice acceleration, a significant decrease in the number of tracks ($p < 0.001$) and the anatomical precision score ($p \leq 0.005$) was observed in the soleus and tibialis anterior muscles.

The overall SNR was 57.3 ± 6.6 in conventional DTI, 45.3 ± 11.2 with two-fold slice acceleration, and 35.1 ± 8.2 with three-fold slice acceleration. However, the SNR per minute increased with higher slice acceleration (conventional DTI: 7.7 ± 1.1; slice acceleration factor 2: 11.7 ± 3.0; slice acceleration factor 3: 13.3 ± 3.1).

Discussion

Simultaneous multi-slice acquisition with blipped-CAIPIRINHA proved feasible for accelerated DTI of skele-

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[1] The product is still under development and not commercially available yet. Its future availability cannot be ensured.
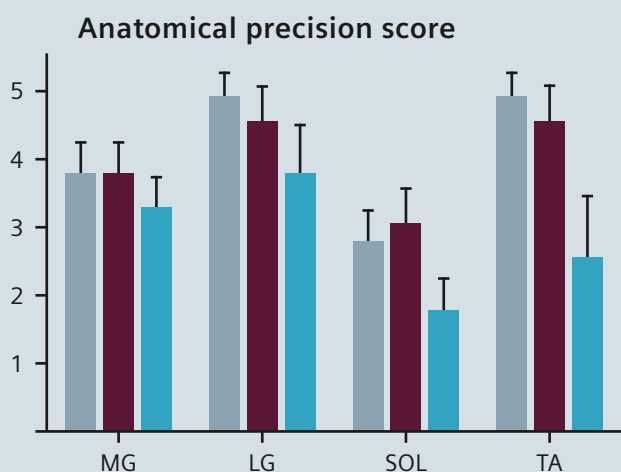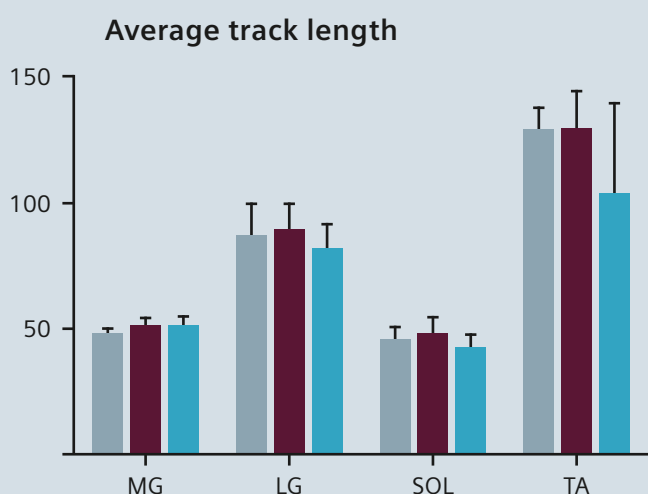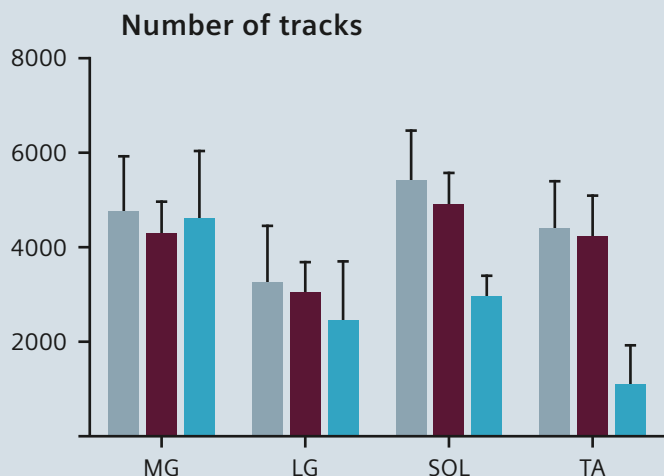
3 Performance of fiber tracking regarding the number of tracks, average track length [mm] and anatomical precision score. SA = slice acceleration. *Used with permission from [1].*

Legend:
- Conventional DTI
- 2x SA
- 3x SA

tal muscle. With the parameters used in our study, a slice acceleration factor of 2 turned out to be the optimal compromise between reduction of acquisition time, quantification accuracy and image quality. Three-

fold slice acceleration was limited by two factors: First, FA values were significantly higher compared to conventional DTI, which may be attributed to the reduced SNR [13, 14]; second, fiber tracking was

impaired regarding number of tracks and anatomical precision, likely due to the lower SNR.

Whereas previous studies used only 6–10 diffusion encoding directions [15-18], we used 20 because recent

works proposed at least 12 or even 20 directions for accurate estimation of anisotropy [19, 20]. In contrast, we only acquired two signal averages (compared to 6-10 in the above-mentioned studies). Additional signal averages would elevate the SNR but do not influence the minimum sampling requirement of the diffusion tensor [21]. With our DTI parameters, all sequences yielded an SNR above the critical threshold of 25 for accurate muscle DTI [19].

The scan time reduction by almost 50% notably increases the clinical applicability of muscle DTI. It can be assumed that simultaneous multi-slice acquisition with blipped-CAIPIRINHA also qualifies for the assessment of tears or hematoma [2-4], where muscle DTI has its greatest potential for clinical application.

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