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Diffusion-direction-dependent imaging: a novel MRI approach for peripheral nerve imaging

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Abstract

A novel magnetic resonance imaging approach, called diffusion-direction-dependent imaging (DDI), is introduced. Due to inherent anisotropic diffusion properties, peripheral nerves can be visualized on diffusion tensor imaging (DTI). The largest signal attenuation on DTI correlates with the direction of a nerve fiber, and the least signal attenuation correlates with the direction perpendicular to the nerve fiber. Since low signal-to-noise ratio is a concern in peripheral nerve DTI, we explored a new approach focusing on the perpendicular diffusion direction. A 36-gradient diffusion direction scheme was used. A mean expected curve specific for peripheral nerves was calculated based on the sciatic nerve and its division into the common peroneal nerve and the tibial nerve in three healthy volunteers. By a simple postprocessing method, a comparison of the mean expected curve and the measured curve was made voxel by voxel, and the sciatic nerve and its division were reconstructed, excluding other tissues. More studies are needed to investigate whether other postprocessing methods or other diffusion direction schemes are more suited for peripheral nerve imaging with DDI. Further studies may also be of interest to investigate whether DDI can be a complementary method to conventional T_1-weighted and T_2-weighted sequences in the imaging of peripheral nerve pathology or even in the visualization of other tissues, possibly with different diffusion direction schemes.

Keywords: Diffusion; Direction; Dependent; Magnetic; Peripheral; Nerve; DDI

1. Introduction

Conventional magnetic resonance imaging (MRI) depicts nerves predominantly due to their anatomical location and not due to specific findings. As nerves have anisotropic diffusion properties, diffusion tensor imaging (DTI) has evolved as a complementary imaging technique of brain white matter [1]. In recent years, it has been shown that peripheral nerves can be visualized by DTI, although the signal-to-noise ratio (SNR) is a limiting factor [2–4]. In DTI, diffusion tensor is calculated from the employment of different gradient diffusion directions. The shape and the rotation of the tensor are described by a 3×3 matrix containing six unique elements, with three elements describing shape (i.e., the eigenvalues) and with three elements describing rotation. The direction of the largest eigenvalue correlates with the direction of the largest diffusion (i.e., along nerve fibers) [5]. Due to the low SNR in peripheral nerve DTI, a limiting factor in a tensor model is that the largest eigenvector (i.e., nerve fiber direction) is in the direction of the largest signal attenuation. This becomes of concern when the diffusion b value forces the signal close to the signal floor. We therefore present an approach that focuses on the diffusion direction perpendicular to the nerve direction, which has the least signal attenuation. In combination with a long b value of 1000 s/mm^2, for background body signal suppression, we have visualized the sciatic nerve and its division into the common peroneal nerve and the tibial nerve in three healthy volunteers. Data are presented as maximum intensity projection (MIP) images based on a single diffusion direction or a postprocessing model based on 36 diffusion directions, which we called diffusion-direction-dependent imaging (DDI).

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2. Materials and methods

2.1. Materials, MRI sequences and diffusion-encoding directions

The distal portion of the left thigh of three healthy volunteers was examined. All participants were placed supine on a 1.5-T Intera MR scanner (Gyroscan Intera; Philips Medical Systems, Best, The Netherlands). The Philips two-channel SENSE Flex-M coil was used. Diffusion imaging was performed in the axial plane with a single-shot diffusion-weighted echo planar imaging (EPI) sequence, a b value of 1000 s/mm^2 in 36 diffusion-encoding directions plus a reference image without diffusion weighting (T_R=6698 ms, T_E=87 ms, slice thickness/gap=4/0 mm, slice=30, field of view=220 mm, matrix=96×128, number of acquisitions=6). The total scan time was 25 min. Sensitivity encoding with a reduction factor of 2 and spectral presaturation with inversion recovery (SPIR) for fat suppression were used. The 36 diffusion-encoding directions are presented in Fig. 1 and Table 1. The first gradient direction is solely in the z-direction (i.e., proximal–distal direction). The following gradient directions are repeated with a 5° inclination in the phase-encoding direction (zy-plane; i.e., in an anterior–posterior plane) until the complete zy-plane has been covered. T_1-weighted anatomical reference images were collected over the same volume of interest.

2.2. Methods for visualizing the sciatic nerve and its division

Two methods for visualizing the nerves were tested: (1) a method including raw image data from a single diffusion direction, and (2) a method combining data from all 36 diffusion directions through a simple postprocessing step.

2.2.1. Visualizing the nerves with a single diffusion direction

The location of the sciatic nerve and its division into the common peroneal nerve and the tibial nerve on axial T_1-weighted images was correlated with axial-diffusion-direction-encoded images. In all three subjects, there was high signal on diffusion images with a gradient direction perpendicular to the nerves, and there was low signal on diffusion images with a gradient direction parallel to the nerves where the nerves were located (Fig. 2). On T_1-weighted consecutive images, the sciatic nerve had, in all three patients, a slight dorsal distal direction in 10 central axial images. Therefore, Direction 18, being perpendicular to that direction, was used for MIP images to visualize nerve fiber bundles.

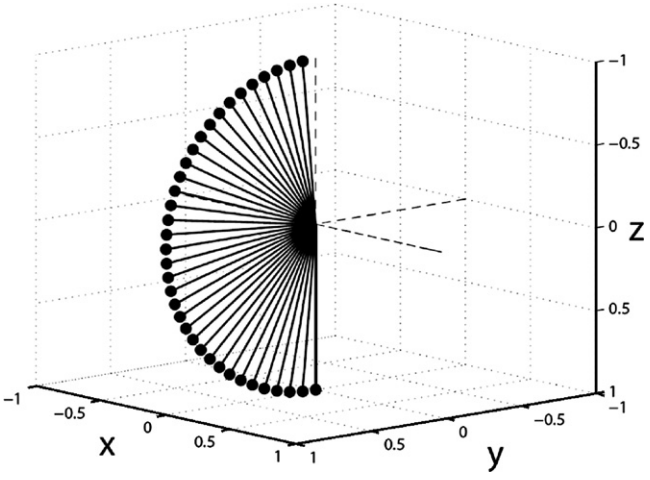

Fig. 1. The 36-gradient diffusion direction scheme. X-axis, left–right direction; y-axis, anterior–posterior direction; z-axis, proximal–distal direction.

Table 1
Index normalized diffusion directions (x, y and z) and spatial angle in the zy-plane for the 36 diffusion-encoding directions seen in Fig. 1

Index	Normalized diffusion directions			Spatial angle (°)
	x	y	z	
1	0	0	1.0000	−90
2	0	0.0872	0.9962	−85
3	0	0.1736	0.9848	−80
4	0	0.2588	0.9659	−75
5	0	0.3420	0.9397	−70
6	0	0.4226	0.9063	−65
7	0	0.5000	0.8660	−60
8	0	0.5736	0.8192	−55
9	0	0.6428	0.7660	−50
10	0	0.7071	0.7071	−45
11	0	0.7660	0.6428	−40
12	0	0.8192	0.5736	−35
13	0	0.8660	0.5000	−30
14	0	0.9063	0.4226	−25
15	0	0.9397	0.3420	−20
16	0	0.9659	0.2588	−15
17	0	0.9848	0.1736	−10
18	0	0.9962	0.0872	−5
19	0	1.0000	0.0000	0
20	0	0.9962	−0.0872	5
21	0	0.9848	−0.1736	10
22	0	0.9659	−0.2588	15
23	0	0.9397	−0.3420	20
24	0	0.9063	−0.4226	25
25	0	0.8660	−0.5000	30
26	0	0.8192	−0.5736	35
27	0	0.7660	−0.6428	40
28	0	0.7071	−0.7071	45
29	0	0.6428	−0.7660	50
30	0	0.5736	−0.8192	55
31	0	0.5000	−0.8660	60
32	0	0.4226	−0.9063	65
33	0	0.3420	−0.9397	70
34	0	0.2588	−0.9659	75
35	0	0.1736	−0.9848	80
36	0	0.0872	−0.9962	85

2.2.2. DDI: method and postprocessing

Each image voxel was acquired with 36 diffusion directions. The signal intensities in a voxel varied with the diffusion direction. This variation was tissue-dependent. Fig. 3 illustrates signal intensity variation, depending on the spatial angle of the diffusion direction in different tissues. In order to visualize the nerve and to suppress all other tissues, a comparison between the expected curve shape ($\hat{x}$)